Managing infiltration and inflow into wastewater systems: Assessing social gains by using probabilistic cost-benefit analysis

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Managing infiltration and inflow into wastewater systems: Assessing social gains by using probabilistic cost-benefit analysis

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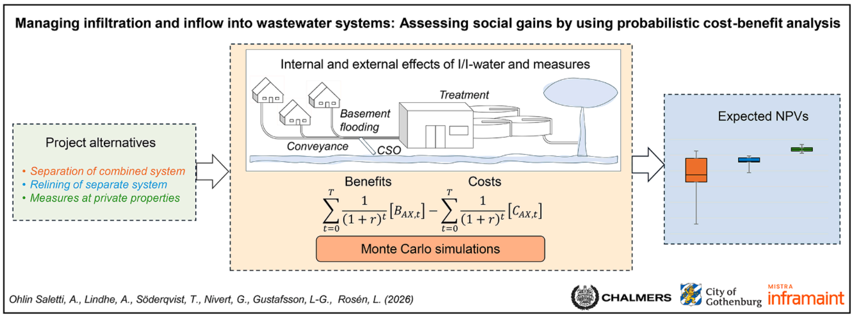
HIGHLIGHTS

- Novel decision support model for infiltration and inflow to wastewater systems.
- Probabilistic cost-benefit approach with expert elicitation and Monte Carlo simulation.
- Includes and monetises 14 effects on water utilities and the rest of society.
- Highlights importance of considering externalities and including uncertainties.
- Enables transparent and structured decision making to benefit society as a whole.

GRAPHICAL ABSTRACT



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ABSTRACT

The wastewater system is an essential part of our infrastructure as it prevents flooding and protects public health and the environment. Infiltration and inflow into wastewater systems (I/I-water) is a significant problem for water utilities and should be managed so that investments maximise benefits to society. This paper presents a decision-support model based on cost-benefit analysis, with the novelty of including and monetising 14 effects of I/I-water measures which either affect the water utility or other parts of society and considering various uncertainties by assigning probability distributions to the input variables and performing Monte Carlo simulations. Currently, no such model is available to quantify the total value to society from measures to handle I/I-water. The proposed model is illustrated in a case study in Gothenburg, Sweden. In the case study, a reference alternative is compared to three conceptual project alternatives: total separation of the combined system, relining of the entire separate sanitary sewer system, and remediation at private properties. The case study highlights an imbalance in the distribution of costs and benefits for the water utility and society and shows the significance of including externalities to avoid underestimating the social benefits of removing I/I-water. Using the presented novel model facilitates a transparent and structured decision-making process for handling I/I-water in the manner most effective to society.

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1. Introduction

Water from infiltration and inflow (I/I-water) is one of the biggest challenges for wastewater systems. In this paper, the term wastewater system refers broadly to the sewer network, including both combined and separate systems, consistent with terminology commonly used in Nordic and European contexts (Ambulkar, 2026). Further, the term I/I-water is also used inconsistently in the literature, sometimes referring to all non-sanitary water in separate or combined systems, extraneous water in separate systems, or other related definitions. In this paper, the first and broader definition is applied, and the implication of this is further discussed in the Discussion section.

The I/I-water share, which increases the need for conveyance and treatment accounts for on average, 30–80% of the annual flows to the wastewater treatment plants (WWTPs) in combined and separate systems in the Nordic countries (Sola et al., 2018). Combined sewer overflow (CSO) spills, which are usually direct effects of I/I-water, lead to the release of pollutants and can pose various ecological and social risks (Perry et al., 2024). Moreover, basement flooding, here referring specifically to sewer back-ups caused by I/I-water overloading the system, is costly to society due to both physical damage and discomfort for those affected (Torgersen and Navrud, 2018). Apart from mitigating these negative effects, other motives for removing I/I-water include: stricter requirements regarding wastewater treatment and CSO spills, e.g. in the European Union’s new urban wastewater directive (European Union, 2024); stricter requirements for the dimensioning of wastewater pipes (e.g. Swedish Water, 2016); and increased urbanisation, which puts a larger load on the system. I/I-water can be decreased through measures such as rehabilitation, for example, renovation and replacement of the piping system, or redirection of flows, for example, separation of combined systems and removal of illicit connections (Ohlin Saletti, 2021).

A vast number of methods for the detection and quantification (e.g. Beheshti et al., 2015; Franz, 2007) and modelling (Karpf and Krebs, 2011; e.g. Perez et al., 2024) of I/I-water have been reported. Specific effects of I/I-water, such as CSO spills, have also been investigated (e.g. Derx et al., 2023), as well as the effectiveness of measures to reduce I/I-water (e.g. Sola et al., 2021; Staufer et al., 2012) and the side effects of the measures themselves (e.g. Kaushal and Najafi, 2020). Despite this extensive theoretical knowledge, I/I-water remains a large concern in many places worldwide.

In the context of decision-making, water utilities, which here refer to the organisations responsible for both the municipal wastewater piping system and WWTPs, need to consider several effects related to I/I-water. Beheshti and Sægrov (2018) and Sola et al. (2020) highlight the importance of adopting a comprehensive approach to analyse effects. This suggests that water utilities’ decision making should account not only for effects traditionally considered (*internal effects*), but also for effects on the rest of society (*external effects*, i.e., externalities). One typical example of such an external effect with respect to the decision-making of water utilities is when they do not (partly or fully) consider the societal consequences of the release of greenhouse gas (GHG) emissions, both when pumping and treating I/I-water but also when constructing the measures.

Besides the broad range of effects that can be incorporated in an I/I-water decision-support model, it is essential to consider the various uncertainties related to each aspect (Beheshti and Sægrov, 2018). Uncertainties may, among other things, result from variations in weather and climate, the state of the existing wastewater system, the effectiveness of the implemented measures, and the effect of I/I-water on society (Ohlin Saletti et al., 2021). Uncertainties can be incorporated using a probabilistic approach where probability distributions are used instead of point values to represent uncertainties due to natural variability and/or lack of knowledge (Bedford and Cooke, 2001).

Cost-benefit analysis (CBA) is a decision-support method that includes both internal and external effects to assess profitability for society as a whole and lends itself to applying a probabilistic approach. Costs and benefits of project alternatives (such as measures to reduce I/I-water) are defined relative to a reference alternative and monetised whenever data availability makes this practically possible (Boardman et al., 2018; Johansson and Kriström, 2018).

Different effects of I/I-water have been included in previous decision-support models, such as the ones by Davalos et al. (2018); Diogo et al. (2018), and Lee et al. (2009), which, however, do not include external effects or use a probabilistic approach. Hansen et al. (2024) and Sola et al. (2020) include some external effects but do not use a probabilistic approach. Vallin (2016) includes internal and external effects and a probabilistic approach to some extent but does not monetise the effects. Probabilistic approaches have been applied to various aspects of analyses of the wastewater system. Wang et al. (2019), for example, focus on I/I-water and model uncertainties but do not include external effects. In the model by Korving et al. (2009) on sewer rehabilitation, external effects related to environmental damage due to CSO spills are included but it does not focus on I/I-water. Consequently, while CBA is widely applied in many policy areas (e.g. HM Treasury, 2026) there is, to our knowledge, no scientifically published model that uses CBA to evaluate I/I-water measures that includes both internal and external effects while also evaluating uncertainties using a probabilistic approach.

The aim of this paper is to develop a novel decision-support model using probabilistic CBA and including both the internal and external effects of I/I-water and mitigation measures. The internal and external effects of I/I-water related to treatment and conveyance, CSO spills, basement flooding, and implementation of measures are included in the model, and uncertainties are assessed by assigning probability distributions representing the input variables and performing Monte Carlo simulations. The model in this paper builds on Ohlin Saletti et al. (2023), where a model for calculating the cost for society of I/I-water was presented. The new model enables the inclusion of costs associated with implementing measures to reduce I/I-water, and it also refines the previous cost calculations and reformulates them as benefits of implementing such measures, thereby resulting in a comprehensive CBA-model. To illustrate the application of the model, a case study is performed where large measures in the wastewater sewer systems in Gothenburg, Sweden, are compared.

2. Method

2.1. Model conceptualisation

The theoretical foundation of the presented model (Fig. 1) follows the risk and decision analysis framework by Ohlin Saletti et al. (2021) and is based on established theories on risk assessment and decision making (e.g. Aven, 2012; ISO, 2018) The risk assessment is set up based on goals, criteria and the preferences of stakeholders, and concludes with an assessment of measures in terms of costs and benefits in a probabilistic CBA as a decision-analysis method. The results of the CBA serve as one input in a managerial review and judgement process, which can lead to a decision or a revision of goals, criteria and preferences.

The costs and benefits of I/I-water result from a chain of events beginning with a risk source that leads to I/I-water and causes further various effects. I/I-water can be categorised as *rain-derived inflow* (RDI), *rain-induced infiltration* (RII), or *groundwater infiltration* (GWI) and enters the wastewater system either on the private or municipal side. The municipal network can be *combined* with one single pipe for both sanitary sewage and stormwater or *duplicate* with the fractions led in separate systems. It should be noted that I/I-water consisting of stormwater from a combined system is the effect of a design choice whereas other kind of I/I-water arise from defects or malfunctions in the system. The effects of I/I-water can be categorised into more continuous effects, such as increased conveyance and treatment, and temporary effects, such as basement flooding and CSO spills. The temporary effects are primarily related to RDI, i.e. the rapid flows of I/I-water.

To alter the effects of I/I-water, mitigation measures can be performed. These can, for example, consist of: relining, which prevents RII and GWI; measures at private properties preventing RDI, RII and GWI; or separation of combined systems, mostly preventing RDI.

Uncertainties are present throughout the chain of events and can relate to variations in rainfall volumes, prerequisites for infiltration and inflow in the system, and the occurrence of specific effects, such as CSO spills etc. Preventive measures are also associated with various uncertainties, e.g. related to their effect on I/I-water levels and the corresponding consequences.

2.2. Model formulation

In order to compare different project alternatives, which can consist of one or several measures, net present values (NPVs) are calculated according to Fig. 2, where *T* is the time horizon including the years *t* ($t = 0 \ldots T$, where 0 denotes the beginning of the first year), $B_{AX,t}$ the sum of the benefits for project alternative *AX* year *t*, $C_{AX,t}$ the sum of the costs for project alternative *AX* year *t*, and *r* the social discount rate. The uncertainty of the results is evaluated by applying a probabilistic approach where probability distributions represent the uncertainties of the included variables. To enable uncertainty and sensitivity analyses, a Monte Carlo simulation is performed.

As presented in Fig. 2, cost and benefit items related to the cost of implementing the measures as well as reduced costs for treatment of I/I-water, conveyance of I/I-water, CSO spills, and basement flooding are included in the model. The costs and benefits are evaluated in relation to a reference alternative, A0. The included cost and benefit items were chosen based on a literature review (Ohlin Saletti, 2021) and the selection was developed during workshops and discussions with experts at water utilities and consultancies. Costs and benefits were chosen to cover the most impactful effects of I/I-water and mitigation measures, but obviously not all possible costs and benefits are included especially when it comes to external effects. Further, several positive effects of I/I-water have been reported, such as increased transport capacity and control of groundwater levels (e.g. Karpf and Krebs (2011); Ohlin Saletti (2021)), but these have not been included at this stage.

An overview of the included cost and benefit items is presented in Table 1 and it is noted if the item was included in the previous model by Ohlin Saletti et al. (2023). The corresponding equations can be found in the following sections (with items expressed in monetary units [MU]). Note that many simplifications have been made in the proposed calculations and that the approaches might not be valid in all applications. However, the equations still provide a valuable foundation for further development and analysis. A list of abbreviations and variables can be found in Appendix A.

2.2.1. Reduced costs for treatment of I/I-water

The annual reduced cost at the WWTP for operation and maintenance is calculated according to Eq. (1):

$$B1_{AX_{yr}} = V_{I/I_{A0}} \cdot s_{I/I_{AX}} \cdot C_{tr} \tag{1}$$

where $V_{I/I_{A0}}$ [m^3/yr] is the volume of I/I-water to the WWTP for A0, $s_{I/I_{AX}}$ [-] (unitless variable) the share of volume of I/I-water to the WWTP after implementing AX, and C_{tr} [MU/m^3] the cost for treating I/I-water at the WWTP. For simplicity, the impact of I/I-water on temperature and treatment efficiency is not considered. The volume of I/I-water can be obtained using flow meters or modelling results.

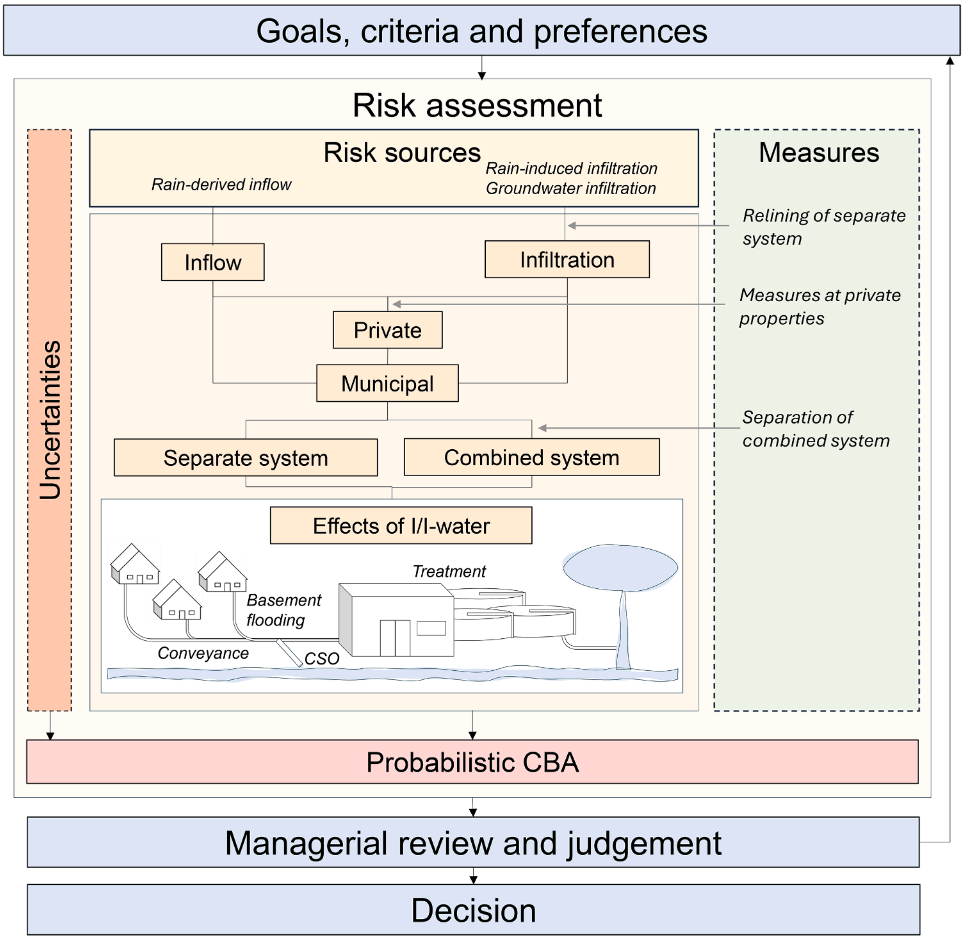

Fig. 1. Conceptualisation of model to assess measures to reduce I/I-water.

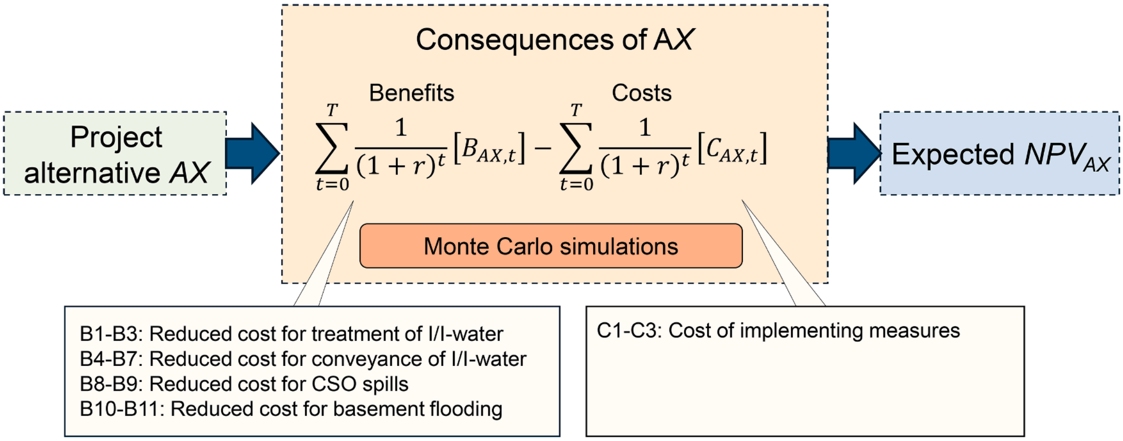

Fig. 2. Cost-benefit model for the calculation of NPVs of project alternatives.

The annual reduced cost for GHG emissions at the WWTP for operation and maintenance is calculated according to Eq. (2):

$$B2_{AX_{yr}} = V_{I/I_{A0}} \cdot s_{I/I_{AX}} \cdot CI_{tr} \cdot C_{CO_2} \tag{2}$$

where CI_{tr} [kg CO_2-eq/m^3] is the climate impact of treating I/I-water and C_{CO_2} [MU/kg CO_2-eq] the social cost of carbon (SCC).

The approach of calculating the benefit of the decreased investment need in the WWTP (B3) depends on whether the measures will result in an alteration to the flow duration curve (FDC) (Fig. 3). If the curve is not altered, the marginal cost approach is applied as described by Ohlin Saletti et al. (2023).

However, if the measures result in a change to the FDC, the benefit is calculated according to Eq. (3):

$$B3_{AX_{yr}} = C_{invA0} \cdot f_{invAX} \tag{3}$$

where C_{invA0} [MU/yr] is the investments in the WWTP for A0 and f_{invAX} [-] a factor describing the investment changes for AX.

2.2.2. Reduced costs for conveyance of I/I-water

The annual reduced pumping cost is calculated according to Eq. (4):

$$B4_{AX_{yr}} = V_{I/I_{A0}} \cdot s_{I/I_{AX}} \cdot E_p \cdot C_p \tag{4}$$

where E_p [kWh/m^3] is the energy consumption for pumping I/I-water and C_p [MU/kWh] the internal costs for pumping I/I-water.

The annual reduced cost for GHG emissions used for pumping is calculated according to Eq. (5):

$$B5_{AX_{yr}} = V_{I/I_{A0}} \cdot s_{I/I_{AX}} \cdot E_p \cdot e_{CO2} \cdot C_{CO2} \tag{5}$$

where e_{CO2} [kg CO_2-eq/kWh] is the climate effect of pumping water.

The following benefit is included when the measures affect the age of the system in a way that alters the renewal rate defined for the reference alternative. In practice, it reflects the internal cost savings achieved by performing fewer rehabilitation actions due to the I/I-measures while still meeting the established renewal targets. The annual reduced cost for renewal is calculated according to Eq. (6):

$$B6_{AX_{yr}} = (r_{A0} - r_{AX}) C_{unit} \cdot l_{tot} \tag{6}$$

where r_{A0} [-] is the renewal rate for A0, r_{AX} [-] the renewal rate for AX, C_{unit} [MU/m] the cost of renewal per meter, and l_{tot} [m] the total length of pipes.

The annual reduced cost for GHG emissions for renewal is calculated according to Eq. (7).

$$B7_{AX_{yr}} = (r_{A0} - r_{AX}) CI_m \cdot C_{CO_2} \cdot l_{tot} \tag{7}$$

where CI_m [kg CO_2-eq/m] is the climate impact for performing the renewal action.

2.2.3. Reduced costs for CSO spills

The cost for CSO spills is divided in two. The first cost is based on the assumption that less stormwater treatment is needed if the CSO spill volume is reduced. For simplification, phosphorus (P) and its corresponding treatment cost is chosen as an indicator for the stormwater treatment cost. This simplification is further discussed in the discussion section. The volume of CSO spills can be obtained using flow meters or modelling results.

The total reduced cost for CSO spills due to reduced need for stormwater treatment is calculated according to Eq. (8).

$$B8_{AX} = V_{CSO\ A0} \cdot s_{CSO\ AX} \cdot C_{tp} \cdot P_{CSO} \tag{8}$$

where $V_{CSO\ A0}$ [m^3/yr] is the annual volume of CSO spills for A0, $s_{CSO\ AX}$ [-] is the share of the annual volume of CSO spills after implementing AX, C_{tp} [MU/g P] the cost of removing P, and P_{CSO} [g P/m^3] the concentration of P in CSO spills.

The second cost of CSO spills is based on the willingness to pay (WTP) to reach good status according to the EU Water Framework Directive in the recipients. WTP can be estimated in different ways, for example through stated-preference or revealed-preference methods. In the following case study, WTP is derived using a stated-preference approach, meaning that the values are based on survey responses rather than observed behavior. As a simplification P and nitrogen (N) are chosen as indicators and the share of the WTP connected to these nutrients is used. Further, to cover the additional share of the WTP related to CSO spills apart from P and N, an additional factor is included.

The annual reduced cost for CSO spills due to increased water quality is calculated according to Eq. (9):

$$B9_{AX_{yr}} = V_{CSO\ A0} \cdot s_{CSO\ AX} \cdot WTP_{gs} \left(s_{PN} * \frac{PN_{CSO}}{t_{r_{PN}}} + s_{ad} \right) \tag{9}$$

where WTP_{gs} [MU/yr] is the total WTP to reach good status in the recipients, s_{PN} [-] the share of the WTP that is related to fulfilling treatment requirements for P and N, PN_{CSO} [g/m^3] the concentration of P and N in CSO spills, $t_{r_{PN}}$ [g/yr] the treatment requirement for P and N, and s_{ad} [-] the share of the WTP that is related to CSO spills excluding the part that relates to reaching target levels of P and N.

2.2.4. Reduced costs for basement flooding

The restoration cost of all basement flooding for a specific return period for the reference alternative A0 is calculated according to Eq. (10a):

Table 1
Cost and benefit items included in the model. "Previous model" refers to the model in Ohlin Saletti et al. (2023).

Cost and benefit item	Description
B1. Reduced costs at WWTP for operation and maintenance	Reduced internal costs for the operation and maintenance of treating I/I-water at the WWTP (Eq. (1)). Included in previous model.
B2. Reduced costs for GHG emissions at WWTP for operation and maintenance	Reduced external costs of the climate impact (expressed in CO_2-eq) from the operation and maintenance of treating I/I-water at the WWTP (Eq. (2)).
B3. Reduced costs for investment in WWTP	Reduced internal costs for investments in the WWTP based on I/I-water flows (Eq. (3)). Included in previous model.
B4. Reduced pumping costs	Reduced internal costs for the electricity used for pumping I/I-water at the wastewater network (Eq. (4)). Included in previous model.
B5. Reduced costs for GHG emissions used for pumping	Reduced external costs of the climate impact (expressed in CO_2-eq) from the electricity used for pumping I/I-water at the wastewater network (Eq. (5)). Included in previous model.
B6. Reduced costs for renewal	Reduced internal costs, incurred when the measures change the age of the system which alters the renewal rate set for the reference alternative. Referring to the internal cost savings from performing fewer rehabilitation actions due to the I/I-measures but still achieving the renewal goals (Eq. (6)).
B7. Reduced costs for GHG emissions for renewal	Reduced external costs which refers to the climate impact (expressed in CO_2-eq) related to performing fewer rehabilitation actions in comparison to the renewal rate set for the reference alternative (Eq. (7)).
B8. Reduced costs of CSO spills due to reduced need for stormwater treatment	Reduced internal costs due to a decreased need for general stormwater treatment to meet the maximum allowable nutrient concentrations in the recipients, based on current environmental quality standards (Eq. (8)).
B9. Reduced costs of CSO spills due to increased water quality	Reduced external costs due to improved status of the recipients, expressed in willingness to pay, when the CSO spills are decreased (Eq. (9)). Partly included in previous model.
B10. Reduced costs of basement flooding due to reduced restoration costs	Reduced internal and external (property owners or insurance companies) costs for rehabilitation due to basement flooding (Eqs. (10a)-b). Included in previous model.
B11. Reduced costs of basement flooding due to reduced discomfort	Reduced external costs of discomfort for households due to basement flooding (Eq. (11a)-b). Included in previous model.
C1. Costs for constructing measures	Internal and external costs to construct the measures. This may include costs related to material, fuel, labour, planning, administrative issues etc., as well as stormwater treatment if stormwater is disconnected from a combined system (Eq. (12)).
C2. Costs for GHG emissions for constructing measures	External costs representing the climate impact (expressed in CO_2-eq) of constructing the measures divided in the categories: production of materials, excavation and asphalt (Eq. (13)).
C3. Costs for traffic delays during construction of measures	External costs based on the extra time (expressed in time value) generated for vehicles passing the construction workplace during the construction of the measures (Eq. (14)).

$$c_{A0res\,rp} = s_{rp_{BF}} \cdot s_{flood} \sum_{b=1}^{B} NB_b \cdot C_{rb} \tag{10a}$$

where $s_{rp_{BF}}$ [-] is the share of basements being flooded during a rainfall with return period rp, s_{flood} [-] the share of buildings in the case study area where basement flooding can occur (based on presence of basement, system type, and topography), NB_b [#] the number of connected buildings of building type b, C_{rb} [MU] the restoration cost of a basement flooding for building type b.

The annual restoration cost of basement flooding for the A0, $C_{BFresA0}$ [MU], is calculated using the integral of the function of $c_{A0res\,rp}$ for all return periods of rainfall. This approach prevents double counting of damages across return periods, a methodological issue discussed in Ohlin Saletti et al. (2023). In practice, the calculations are simplified by choosing a few return periods and assuming linear connections.

The annual reduced cost of basement flooding due to reduced restoration costs is calculated according to Eq. (10b):

$$B10_{yr} = C_{BFresA0}\left(s_{com} \cdot dec_{com_{AX}} + (1 - s_{com})dec_{sep_{AX}}\right) \tag{10b}$$

where s_{com} [-] is the share of basement flooding that occurs in the combined system, $dec_{com_{AX}}$ [-] the decrease of basement flooding in the combined system for project alternative AX, and $dec_{sep_{AX}}$ [-] the decrease of basement flooding in the separate system for project alternative AX.

The cost of discomfort of all basement flooding for a specific return period for the reference alternative A0 is calculated according to Eq. (11a):

$$c_{A0\,dis\,rp} = s_{rp_{BF}} \cdot s_{flood} \sum_{b=1}^{B} NB_b \cdot WTP_{bf_b} \cdot yrs \tag{11a}$$

where WTP_{bf_b} [MU] is the WTP per flooded building and year to avoid basement flooding and yrs the number of years the WTP lasts for.

The annual discomfort cost of basement flooding for the reference alternative, $C_{BFdisA0}$ [MU] is calculated using the integral of the function of $c_{A0\,dis\,rp}$ for all return periods of rainfall in the same way as for B10.

The annual reduced cost of basement flooding due to reduced discomfort costs is calculated according to Eq. (11b):

$$B11_{yr} = C_{BFrdisA0}\left(s_{com} \cdot dec_{com_{AX}} + (1 - s_{com})dec_{sep_{AX}}\right) \tag{11b}$$

2.2.5. *Cost of implementing measures*

The total cost for constructing the measures is calculated according to Eq. (12):

$$C1 = N_{unit} \cdot C_{unit} + C_{ad} \tag{12}$$

where N_{unit} [#] is the number of units to be constructed, C_{unit} [MU] the construction cost per unit, and C_{ad} [MU] additional costs to implement the measure.

The total cost for GHG emissions for constructing measures is calculated according to Eq. (13):

$$C2 = N_{unit} \cdot CI_m \cdot C_{CO_2} \tag{13}$$

The total cost for traffic delays during the construction of measures is calculated according to Eq. (14). Vehicle hours (vh) refers to the extra time that is generated due to construction work. Eq. (14) follows:

$$C3 = \ TV \cdot t_v \cdot tr \cdot \frac{N_{unit}}{con_{pace}} \tag{14}$$

where TV is the time value [MU/vh], t_v [h] is the extra time per vehicle, tr [vehicle/h] the number of vehicles passing by per hour, and con_{pace} [m/h] the pace at which construction progresses.

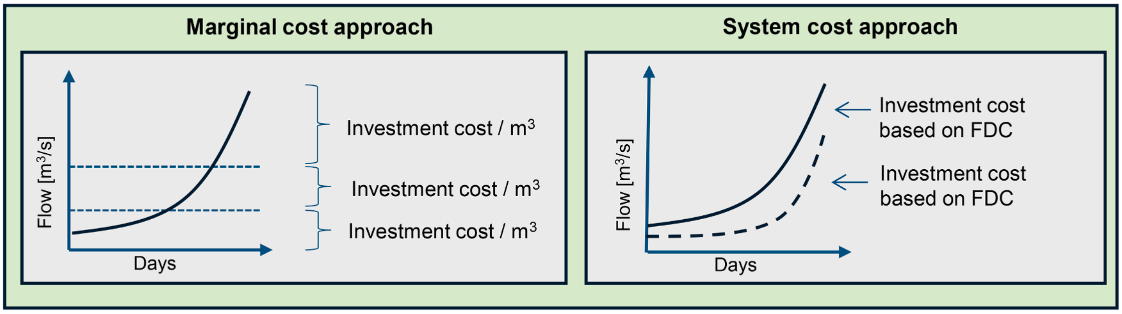

Fig. 3. Schematic figure of the principle of calculating the investment costs in the WWTP related to the flow duration curve (FDC).
Note: The marginal cost approach is used when the measures do not alter the FDC. The cost for investments related to I/I-water is then calculated using investment cost/m^3 for chosen capacity levels in the WWTP. In the system cost approach, the measures are extensive and alter the FDC. The cost for investments related to I/I-water is then calculated by comparing which investments are needed to treat the water for the specific FDC.

2.3. Model application

The model is demonstrated using a case study in Gothenburg, Sweden (Fig. 4). Gothenburg is located on the west coast and had approximately 613,500 inhabitants in 2025. The wastewater system was built mainly during the period 1960–1980. Of the 1400 km of gravity pipes transporting wastewater to the Rya WWTP, about one third is a combined system. The Rya WWTP was built in the 1970s and receives 80% of its flow from the city of Gothenburg, while the rest comes from surrounding smaller municipalities. In 2022, the Rya WWTP received 88.8 million m^3 of water from the city of Gothenburg, of which 40 million m^3 was I/I-water. On some days, RDI may account for as much as 60% of the total flow to the WWTP. Substantial upgrades of the WWTP are planned in the near future and the I/I-water flow affects the design of the new WWTP. Further, I/I-water resulted in 227 000 m^3 sanitary sewage to the receiving water bodies in 2023 due to CSO spills.

The project alternatives in the case study were chosen to demonstrate the use of the model by evaluating how society is affected by full-scale implementation of common measures to decrease I/I-water (A1: separation of the combined system, A2: relining of the separate system,

Fig. 4. Location of case study area.

and A3: remediation of connections on private properties). In practice, a water utility rarely choses between these kinds of full-scale options and these large changes are best described as conceptual. The project alternatives are compared to a A0 which represents the continuation of the current state.

Project alternative A1 refers to separation of the entire combined system (∼400,000 m), i.e. a new pipe for sanitary sewage and one for stormwater are constructed. It is assumed that the separation is performed using open-cut techniques and the construction time is from 2025 to 2075 (50 years). A less outdated option using low impact development or sustainable urban drainage systems could have been chosen but as full-scale separation projects still sometimes are suggested by decision-makers at water utilities, the option of building two separate underground systems was chosen. The cost of performing this measure included separation of the municipal network, separation of the private network, reconfiguration of the road drainage system as well as a cost for building stormwater treatment for the stormwater that is currently led directly to the receiving water bodies.

Project alternative A2 refers to relining of the entire separate sanitary sewer system (∼1000,000 m). It is assumed that the relining is performed using no-dig techniques and the construction time is from 2025 to 2055 (30 years). After the relining the sewer system is considered to have been renewed, which affects the renewal rate, as this assumption is practice in the City of Gothenburg.

Project alternative A3 refers to investigation, performed by the water utility using coloured water and filming, of all properties connected to the separate wastewater system (∼72,000) to see which has roof drains connected to the sanitary sewage or in other ways contribute with I/I-water. If I/I-water contribution is discovered, the property owners are obliged to correct the faulty parts of the private system. The time frame of the project alternative is from 2025 to 2055 (30 years). The cost to perform this project alternative includes the cost for the water utility to perform the investigation as well as the cost for private property owners to perform the remediation. Cost of enforcement is not included, nor external costs related to the remediation by the property owners such as discomfort of being forced to intervene in their gardens. It should be noted that for A1 and A2 the construction costs are borne primarily by the water utility, whereas for A3 the largest share of the cost is borne by private property owners.

To assess the impact of the alternatives on the wastewater system, an existing well-calibrated hydraulic and hydrologic network model of the sewage system in Gothenburg was used (Future City Flow, 2022). Model calibration was based on extensive local measurements, including approximately 10 years of data from 16 permanent flow meters, several years of data from three permanent level meters in tunnels, and a supplementary four-month measurement campaign using 10 temporary flow meters. The total volume of I/I-water as well as CSO spill volumes are based on long term simulations which includes rainfall runoff modelling based on a continuous hydrological modelling approach accounting for soil moisture variations, actual evapotranspiration and snow melt. This is crucial in order to account for the hydrological memory from preceding events, heavily affecting the response of inflow and infiltration during different seasons of a year. Further, the share of the I/I-water volume originating from private properties, RDI, RII, and GWI, and the separate or combined system, are based on assumptions. Depending on the area characteristics, 30–70% of the sum of the RII and GWI components are assumed to come from private properties, and 38% of the properties in the separate system are assumed to have faulty connections which contribute to RDI.

The impact of the measures was evaluated based on the change in I/I-water volumes, CSO spill volumes, and the share of basements being flooded. The change in the share of basements being flooded was based on the result from a simplified version of the hydraulic model evaluating single rain events. It is assumed that all I/I-water is removed from the combined areas when separating the combined system and that remediation on private properties removes all I/I-water coming from private properties. Regarding relining, it is assumed that the most likely effect is 30% of the full effect of removing all infiltration. This is because studies show that relining often does not have the intended effect (Sola et al., 2021; Staufer et al., 2012).

Input variables used in the case study not obtained from the hydraulic and hydrologic model come from the water utility, the literature, and results from expert elicitation according to the SHELF protocol, using a Bayesian statistical approach to uncertainty representation, performed in 2022 and presented in Ohlin Saletti et al. (2023). Variables used in the case study, along with their corresponding probability distributions, are presented in Appendix B. The parameter estimates are site-specific, reflecting local system characteristics, data availability, and expert judgement, and should therefore not be transferred directly to other locations without appropriate adjustments. All monetary amounts are stated in Swedish kronor (SEK) in 2023 prices (1 SEK corresponds to approximately 0.11 EUR (2023)). A 100-year time horizon was chosen, from 2023 to 2122, to include investments in a more distant future and the long lifespan of wastewater pipes. Uncertainty analysis is performed by means of Monte Carlo analysis using the Excel add-in software @Risk (v.8.2) and all runs of the CBA-model for the case study were executed using 100,000 iterations.

As to the choice of discount rate, CBA applications in Sweden typically apply a 3.5% rate recommended by the Swedish Transport Administration (2024), i.e., a constant rate over time. However, internationally it is not uncommon to use a decreasing discount rate over time (e.g. HM Treasury, 2026). In the sensitivity analysis, the consequences of such an alternative discounting were analysed by using the recommendations in the recently suggested CBA guidelines in the U.S. (OMB, 2023): 2% from 2023–2079 and then decreasing to 1.1% in 2164. Further, the sensitivity analysis includes scenarios in which the construction period for the project alternatives is set to either 30 years or 50 years. The sensitivity analysis also includes Spearman's rank-order correlation, a non-parametric measure of the strength and direction of monotonic associations between two variables. This method is used to identify which input variables have the greatest influence on the model results, including cases where the relationships are non-linear.

3. Results

3.1. *Case study results*

Project alternative A1 is found to result in the largest total benefits but also in the largest total costs among the project alternatives (Fig. 5). The opposite applies to A3, which has the smallest benefits but also the smallest costs. Comparing costs and benefits shows that A1 and A2 have negative mean NPVs (−6109 million SEK and −2022 million SEK, respectively), indicating they are not economically beneficial, whereas A3 has a positive mean NPV (1767 million SEK), indicating it is beneficial for society. Further, the probability that the NPV is positive is 20% for A1, 3% for A2, and 98% for A3. The uncertainty intervals (P05-P95) for A1 and A2 both lie fully in the negative range for the NPVs, except for the upper tail of A1, which occasionally produces a positive outcome. In contrast, A3's interval lies entirely above zero, indicating a robustly positive societal net benefit. Taken together, both the mean values and the distribution of outcomes consistently indicate that A3 performs best when considering both expected value and risk.

Fig. 6 shows the cumulative NPVs for the project alternatives throughout the time horizon. The curve for A1 exhibits a steep initial decline and a notably wide uncertainty interval. In contrast, the uncertainties for A2 are narrower, yet its cumulative NPV remains consistently negative across the distribution. A3 displays a distinctly different pattern, its cumulative NPV increases steadily over time, with comparatively limited uncertainty, and the mean value becomes positive after approximately 2050. For A1 and A2, the NPVs remain negative for the entire period for P25 to P75.

Observing the contribution of the individual costs and benefits

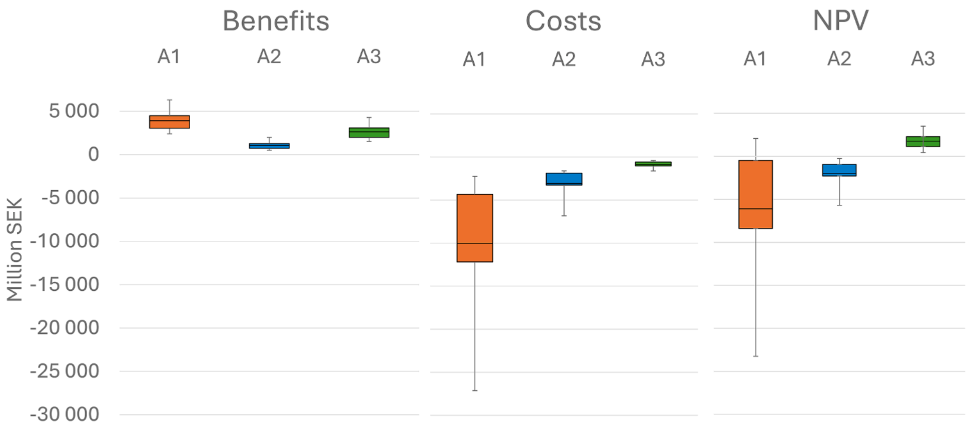

Fig. 5. Benefits, costs and NPV of project alternatives. Bars show P25, mean values and P75, while whiskers show P05 and P95.

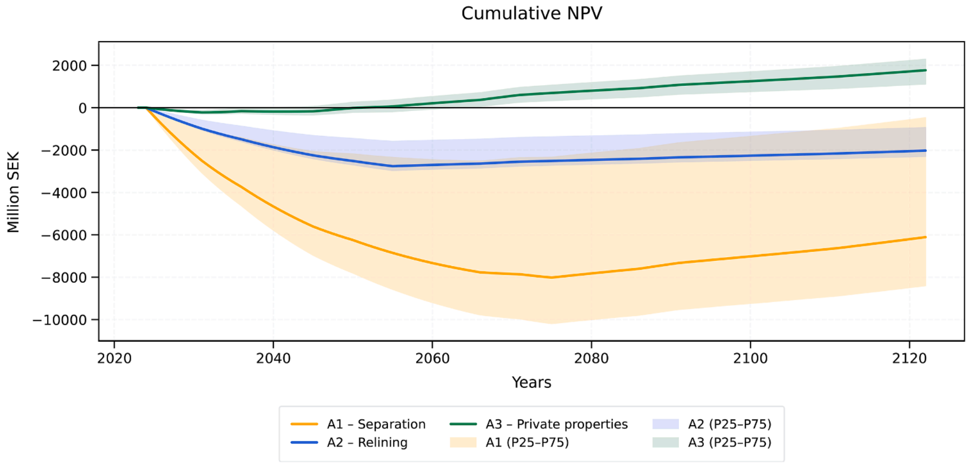

Fig. 6. Cumulative NPV for included measures. Lines represent mean values and shaded areas represent intervals from P25 to P75.

(Fig. 7) it is evident that the internal construction cost (C1) is the most substantial contributor to the overall result, especially for A1. Among the benefits, those relating to the WWTP (B1, B2, B3) and, to some extent, external pumping costs (B5) are large contributors for all project alternatives. Further, the costs related to CSO spills (B8, B9) are large contributors to the total benefit of A1 and the cost of restoration due to

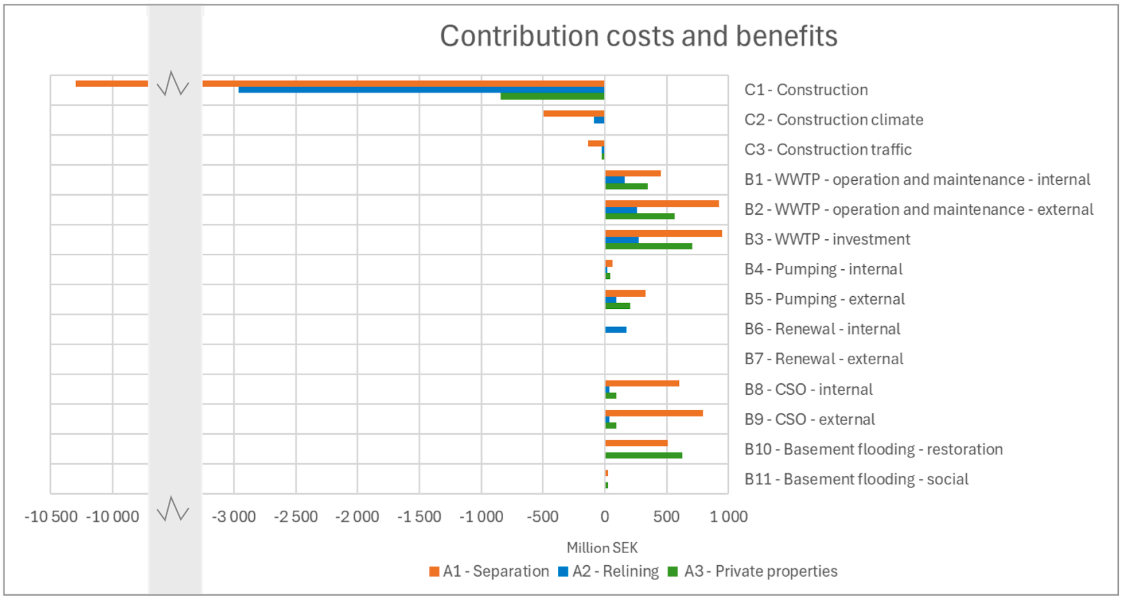

Fig. 7. Contribution of individual costs and benefits. Mean values are shown in the figure.

basement flooding is a large contributor for A1 and A3.

Fig. 8 shows how internal versus external benefits contribute to the results. Regarding the benefits, 37–48% of the total benefits are internal for the water utility (B1, B3, B4, B6, B8 and half of B10[1]). The rest of the benefits are related to climate (B2, B5 and B7) or other external elements (B9, half of B10, and B11). This implies that a substantial share of the benefits from I/I-water mitigation arises from avoided climate damages and reduced societal impacts from CSO spills and basement flooding, rather than from direct cost savings for the water utility. In contrast to this, a large share of costs (94–97%) is related to internal or direct external costs. Direct external costs refer to separation at private properties and reconfiguration of the road drainage system for A1 and remediation on private properties for A3. If only climate impacts are considered, the climate benefits of all project alternatives are larger than the climate costs, e.g. the present value of the climate benefit for A1 is about 1,263 million SEK, while the climate cost is about 138 million SEK. This implies that, from a climate perspective, each alternative delivers a societal net gain, as the avoided emissions substantially exceed the emissions associated with implementing the measures.

3.2. Sensitivity analysis

Fig. 9 presents the NPVs of the project alternatives for the scenarios with constant discount rate (3.5 %) and decreasing discount rate (2 % to 1.1 %), and for construction periods of 30 and 50 years. Across all scenarios, the ranking of the mean NPVs remains the same, with A3 showing the highest mean NPV, followed by A2 and A1. It is also shown that longer construction periods lead to increased mean NPVs for A1 and A2. This, since these alternatives to a high extent are cost driven and with longer construction periods, costs are pushed further into the future and are thereby discounted to a higher extent. Due to the same reason, an increased discount rate also results in increased NPVs for A1 and A2. On the contrary, the mean NPV for A3 is decreased with a longer construction time as well as with an increased discount rate. This, since A3 to a higher extent, is affected by the benefits which in these cases are more discounted. Hence, assuming longer construction periods and higher discount rates favor A1 and A2 in relation to A3. Further, it can be noted that the uncertainties also decrease with increased construction times and discount rates for all project alternatives, as increased discounting reduces the influence of highly uncertain long-term costs and benefits on the NPV.

In Fig. 10 Spearman rank correlation coefficients with an absolute value greater than 0.2 are shown. Coefficients below this threshold indicate weak monotonic relationships and were omitted to improve readability and focus on the most influential parameters. First, it can be noted that among the approximately 50 included uncertain parameters only a few is shown to have a monotonic relationship with the NPVs with an absolute value larger than 0.2 on the Spearman rank correlation coefficient. For all project alternatives the construction cost has a negative correlation to the result. This is particularly obvious for A1, for which the construction cost per meter shows an almost perfect negative correlation with the NPV. All other parameters have Spearman rank correlation coefficients below 0.2, indicating only limited correlations with the result for this project alternative. For A2 and A3, the volume of I/I-water before the measure shows a non-negligible Spearman rank correlation with the NPVs. In addition, for A3, the share of buildings where basement flooding may occur also exhibits a non-negligible monotonic association with the result. Overall, the sensitivity analysis indicates that uncertainty in the NPVs is driven by a small number of key parameters, while the majority of inputs have only a limited influence on the results.

4. Discussion

4.1. Interpretation of the case study results

The project alternatives considered in the case study are conceptual and in real-world applications, the proposed measures would need to be combined, and other types of interventions included to achieve optimal outcomes. Further, the NPV for the project alternatives constitutes only one input to the decision-making process, and additional considerations must be incorporated before selecting a measure. For example, the water utility of the City of Gothenburg has set a goal that there should be a maximum annual release of 90,000m^3 sanitary sewage from CSO spills to the city's largest river. The model shows that, without any measure, it is about 25% certain that the goal will be achieved. Implementing project alternative A1 would achieve the goal with a certainty of 100%, while it is only about 30% and 40% certain for project alternatives A2 and A3, respectively. Therefore, although project alternative A1 has the lowest mean NPV, it is the measure that contributes the most to achieving this goal set by the water utility. If such a goal is taken for granted, a cost-effectiveness analysis could be applied to investigate which project alternative achieves the goal at the lowest cost. Such an analysis should, however, also be performed with care and be seen as one input in the decision-process, since it is possible that the set goal may not be cost-effective from an economic, social, or environmental perspective.

Although the purpose of the case study was to demonstrate the applicability of the model, and that the outcome is highly dependent on the set up of the project alternatives and chosen simplifications, some key findings are discussed below. First, a significant insight from the analysis is that while a large share of the costs associated with I/I-water mitigation measures is internal to the water utility, the benefits are external to a much higher extent. This highlights a structural mismatch between who bears the costs and who receives the benefits. When only internal aspects are considered, as is commonly the case in practice, the societal benefits of I/I-water measures are substantially underestimated, making project alternatives appear less cost-effective than they are from a broader societal perspective.

Further, the results show that, regardless of the choice of discount rate and project time, project alternative A3 is the most cost-effective for society while performing A1 is, by far, the least cost-effective. Focusing on removing I/I-water from private properties (A3) is already current practice in many communities. Yet, in regard to this project alternative it should be noted that the implementation can be difficult. For example, although water utilities in Sweden have the legal right to enforce remediation among connected private properties (ABVA, 2006), this has proven to be challenging in practice due to the difficulties in compelling (forcing) the property owners to carry out the rehabilitation, and later to ensure that it has been done properly (Lundblad and Backö, 2014). Regarding sewer separation (A1), full-scale separation has long been considered a cost-ineffective measure, yet it is still recurrently proposed by decision-makers as a long-term, system-wide approach to reducing I/I-water and its effects (see e.g. Ballerup Municipality (n.d.); Ruderdal Municipality (n.d.)). It should be noted, however, that targeted and carefully selected separation projects, supported by site-specific investigations, may still be economically viable.

In the presented model, a probabilistic approach is applied, where probability distributions represent uncertainties in input variables and total uncertainty is reflected in the results. The case study demonstrates that the NPVs for all project alternatives are associated with substantial uncertainties, mainly related to construction cost, volume of I/I-water, and where basement flooding may occur. These uncertainties indicate that the water utilities lack sufficient knowledge on the practical functioning of the wastewater systems, even though there exist a vast number of theoretical methods on how to detect, quantify and model I/I-water. While it is impossible to eliminate all uncertainties, many can be decreased by using systematic methods including data gathering, field

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[1] It is assumed, based on historic data from the water utility, that half of the number of restoration costs of basement flooding is paid by the water utility and half by the private property owners or their insurance companies.

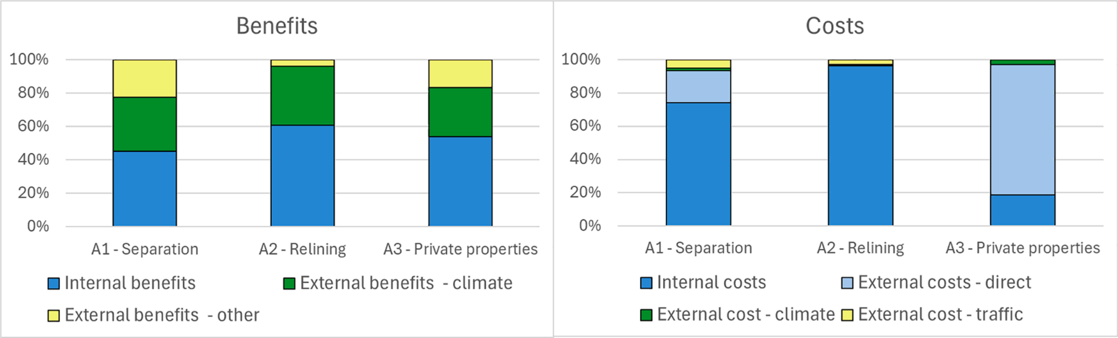

Fig. 8. Proportion of costs and benefits relating to internal and external costs/benefits. External costs – direct refers to financial construction costs paid by others than the water utility.

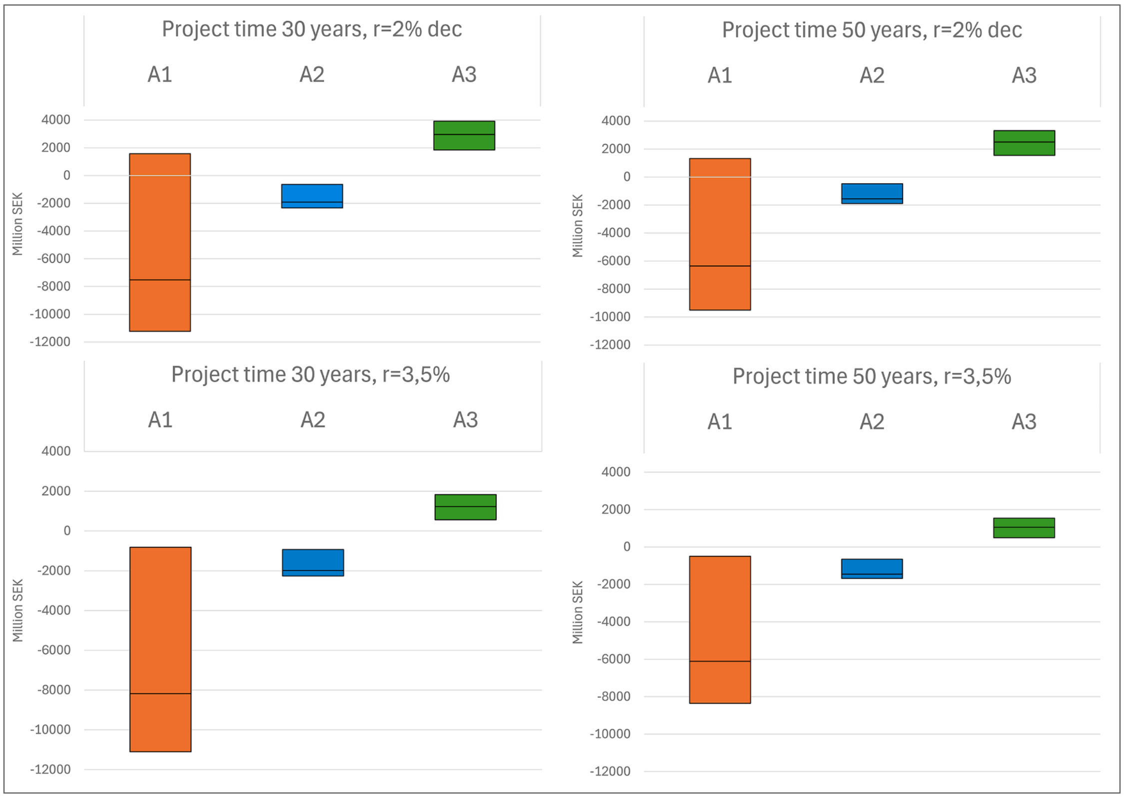

Fig. 9. NPVs of project alternatives using scenarios with constant discount rate 3.5% and discount rate 2% from 2023–2079 and then decreasing to 1.1% in 2164 (called 2% dec in figure) as well as project time 30 and 50 years. Bars show P25, mean values (black line) and P75.

measurements, qualitative and quantitative methods, and evaluation, as suggested by (Beheshti and Sægrov, 2018). However, it must be noted that systematic approaches like these require a budget, time and personnel resources (Malm et al., 2011). An assessment of the benefits of the new information compared to the cost of obtaining it is therefore important for effective management of I/I-water in wastewater systems.

In addition to the parameter uncertainties mentioned above and included in the uncertainty analysis, the results are also affected by model uncertainties. These model uncertainties relate to both the formulation of the presented model and to the hydraulic model, which provides data on how the project alternatives affect the volume of I/I-water, the volume of CSO spills, and the number of basement floods. The results from the hydraulic model regarding how the measures reduce basement floodings are particularly uncertain, since these results originate from the interpretation of a simplified version of the model. The hydraulic model itself is set up using assumptions from the water utility, and considerable uncertainty arises from the assumptions about the share of I/I-water coming from the municipal versus the private side, as well as from faulty connections.

4.2. Model scope, adaptability, and future development

The decision support model presented in this paper builds on the previous work by Ohlin Saletti et al. (2023) where a model for calculating the social cost of I/I-water is presented. The model presented in this paper incorporates those costs, here treated as benefits associated with the removal of I/I-water, while additionally accounting for the costs of implementing I/I-water mitigation measures. As a result, a comprehensive CBA-model is obtained, enabling systematic evaluation of I/I-water measures in relation to their associated benefits.

CBA provides a structured approach to complex decision-support problems. Nevertheless, it has been criticised for assuming that

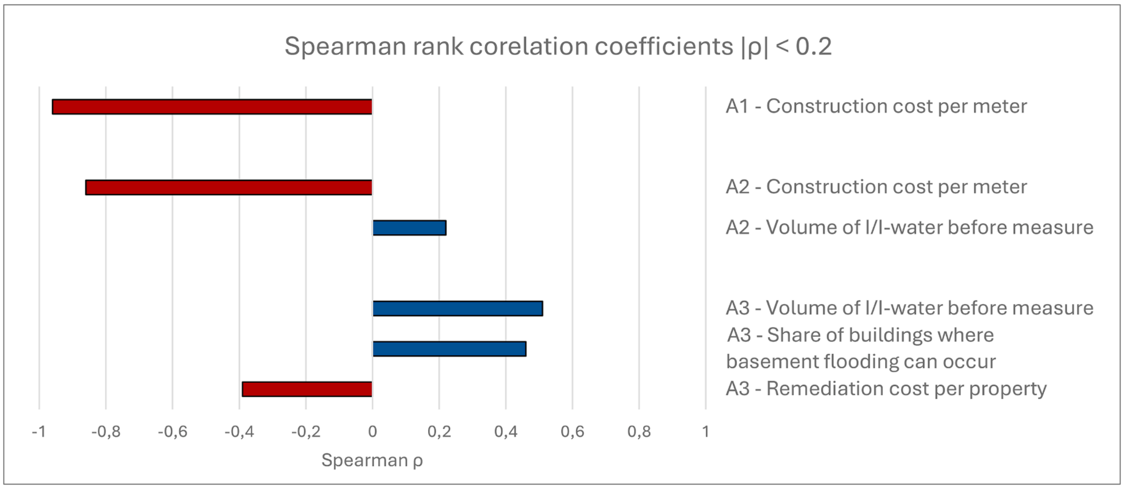

Fig. 10. Spearman rank correlation coefficients of the variables with the greatest influence on the results of project alternative A1, A2 and A3.

fundamentally different impacts can be meaningfully aggregated and that measures are mutually substitutable. This critique is equally relevant when applying the method to I/I-water and the substitutability regarding different flow component and their corresponding consequences must be acknowledged in relation to local contexts and regulatory conditions. The model should be regarded as a flexible framework and while a set of cost and benefit components is proposed for inclusion, their selection and parameterisation should be guided by local characteristics and policy requirements. For example, simplifications have been made when calculating the cost of CSO spills e.g. regarding the choice of using WTP estimates as well as choosing P and N as indicators. This was done partly to reflect local conditions and practices, and to enable the monetisation of external effects that are not commonly quantified. In other contexts, and with more data available, other equally important factors related to CSO spills such as oxygen depletion due to BOD loads, toxicity on unionised ammonia, and hydraulic stress can be more specifically accounted for. In general, the calculation methods presented can serve as a useful point of departure, however, they must be applied with critical judgment, as several underlying assumptions and simplifications may not be valid in all settings. When used in this way, the framework can enhance both the structure and transparency of decision-making processes related to I/I-water management, helping to clarify trade-offs that might otherwise remain implicit.

As noted previously, the definition of I/I-water has been the subject of debate. In this model, a broad definition is applied, where the term I/I-water encompasses “all water in both combined and separate sewer systems that is not sanitary sewage”. However, the model’s application is not limited to this definition. The selection of measures and their impact on I/I-water related outcomes, such as flow volumes or the frequency of basement flooding, are determined based on the specific case and used as input in the model. Consequently, the model can be applied even under alternative definitions of I/I-water, focusing solely on a specific system (e.g., separate sewers) or a particular type of water (e.g., infiltration only). Further it is worth to emphasize that a key feature of the proposed model is that it consistently includes both internal and external costs, which may differ from how costs are typically handled in practice. In some regions, backwater valves are mandatory on private properties and can reduce the likelihood of basement flooding. Additionally, water utilities are only responsible for damages up to a specific design flow. However, it is the actual damage cost due to I/I-water that should be included in the model irrespective of whom is responsible as the model focuses on the cost for society as a whole.

To develop the model further and capture more aspects, different scenarios regarding population growth, the impact of climate change, technological development etc., can be included within the chosen time horizon of 100 years. Although the time horizon used is long, the choice of a shorter period could lead to wrong decisions as measures with long technical lifetimes may be systematically disadvantaged when their benefits extend beyond the period selected for the analysis. Furthermore, elements from the presented model can also be combined with existing models to include additional dimensions in the decision-making, for example in optimisation models focusing on remediation needs of individual pipe segments. Moreover, to capture aspects not considered within a CBA because of its specific ethical and theoretical foundations, the suggested model can be complemented by, or integrated into, other decision-support methods, e.g. multi-criteria decision analysis (MCDA) as suggested by (Söderqvist et al., 2015). In a MCDA, aspects difficult to monetise can be added, as shown by (Scholten et al., 2014), who use the rehabilitation rate of the water network to represent intergenerational equity.

5. Conclusions

The main conclusions of this paper are:

- Evaluating I/I-water mitigation measures using a probabilistic cost–benefit approach can substantially change how such measures are interpreted and prioritised. By explicitly including uncertainty and the fact that costs and benefits fall on different actors, it becomes clear that relying only on deterministic and internal costs can lead to misleading conclusions from a societal point of view.
- The case study highlights a structural mismatch in the distribution of costs and benefits of I/I-water mitigation, where costs are largely borne by water utilities while a substantial share of the benefits is borne by society. As a consequence, decision making that focuses only on internal effects risks biasing priorities against I/I-water mitigation measures, since their socially important benefits largely occur outside the water utility.
- For the specific case study application, remediation of faulty connections at private properties was found to be the most cost-effective I/I-water mitigation measure, followed by relining, while full-scale separation was the least cost-effective but also associated with the highest uncertainty. However, it should be noted that costs for remediation of private properties are primarily borne by property owners, whereas separation and relining costs are mainly borne by the water utility.
- The proposed model provides a transparent and structured basis for decision support in I/I-water management, offering information that is not usually considered in practice. Its flexible design allows for

further development, including additional effects, utility goals, future scenarios, and integration with optimisation or multi-criteria decision analysis frameworks.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGTP and Copilot to edit and revise the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Anna Ohlin Saletti: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Andreas Lindhe:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Tore Söderqvist:** Writing – review & editing, Validation, Methodology. **Glen Nivert:** Writing – review & editing, Validation, Supervision, Methodology. **Lars-Göran Gustafsson:** Writing – review & editing, Validation, Resources. **Lars Rosén:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A Abbreviations and notations

Table A1
Abbreviations used in the paper.

Abbreviation	Meaning
CBA	Cost–Benefit Analysis
CO_2-eq	Carbon dioxide equivalent
CSO	Combined Sewer Overflow
FDC	Flow Duration Curve
FCF	Future City Flow (hydraulic and hydrologic model)
GHG	Greenhouse Gas
GWI	Groundwater Infiltration
I/I	Infiltration and Inflow
MCDA	Multi-Criteria Decision Analysis
MU	Monetary Unit
N	Nitrogen
NPV	Net Present Value
P	Phosphorus
RDI	Rain-Derived Inflow
RII	Rain-Induced Infiltration
SCC	Social Cost of Carbon
SEK	Swedish Krona
SHELF	Sheffield Elicitation Framework
WTP	Willingness To Pay
WWTP	Wastewater Treatment Plant

Table A2
Notations used in the paper.

Variable	Description [unit]
A_{as}	Asphalt area per meter [m^2/m]
C_{ad}	Additional cost to perform a measure [MU]
cap	Capacity of the truck transporting masses [kg/truck]
$C_{BF\ dis\ A0}$	Annual cost of basement-flooding discomfort for A0 [MU/yr]
$C_{BF\ res\ A0}$	Annual restoration cost of basement flooding for the A0 [MU/yr]
C_{CO2}	Social cost of carbon [MU/kg CO_2-eq]
$C_{inv\ A0}$	Investments in the WWTP for A0 [MU/yr]
C_p	Internal costs for pumping I/I-water [MU/kWh]
C_{tp}	Cost of phosphorus removal [MU/g P]
C_{tr}	Cost of treating I/I-water at the WWTP [MU/m^3]
C_{rb}	Cost restoration of a basement flooding for building type b [MU]
C_{unit}	Construction/renewal cost per unit [MU/m or MU/unit]
con_{pace}	Pace at which construction progresses [m/h]
CI_{as}	Climate impact of demolishing the old and paving the new asphalt [kg CO_2-eq/m^2]
CI_{ex}	Climate impact of excavation [kg CO_2-eq/h]

(continued on next page)

Table A2 (*continued*)

Variable	Description [unit]
CI_m	Climate impact per meter [kg CO_2-eq/m]
CI_{pipe}	Climate impact of pipe material [kg CO_2-eq/m]
CI_{tp}	Climate impact of transportation during construction [kg CO2-eq/km]
CI_{tr}	Climate impact of treating I/I-water [kg CO2-eq/m3]
d_{as}	Asphalt depth [m]
$dec_{com\ AX}$	Decrease of basement flooding in combined system [–]
$dec_{sep\ AX}$	Decrease of basement flooding in separate system [–]
$dist$	Transport distance [km]
e_{CO2}	Climate effect of pumping water [kg CO_2-eq/kWh]
E_p	Energy consumption for pumping I/I-water [kWh/m^3]
f_{ad}	Share of separation cost for private network and rerouting [–]
$f_{inv\ AX}$	Factor describing the investment changes at WWTP for AX [–]
l_{tot}	Total pipe length [m]
N_{PO4eq}	Conversion factor N to PO_4 [–]
N_{ss}	Concentration of N in sanitary sewage [g/m3]
N_{sw}	Concentration of N in stormwater [g/m3]
N_{unit}	Number of constructed units [#]
NB_b	Number of buildings of type b [#]
P_{CSO}	Phosphorus concentration in CSO [g P/m^3]
P_{ex}	Excavation production rate [m^3/h]
$P_{PO4\ eq}$	Conversion factor P to PO_4 [–]
P_{ss}	P concentration in sanitary sewage [g/m^3]
P_{sw}	P concentration in stormwater [g/m^3]
PN_{CSO}	PN concentration in CSO spills [g/m^3]
r	Social discount rate [–]
r_{A0}	Renewal rate for A0 [–]
r_{AX}	Renewal rate for AX [–]
$reuse$	Share of reusable mass [–]
r_{rate}	Reduction rate P in stormwater treatment [-]
s_{ad}	Share of the WTP that is related to CSO spills excluding the part that relates to reaching target levels of P and N [–]
s_{com}	Share of basement flooding in combined system [–]
$s_{CSO\ AX}$	Share of the annual volume of CSO spills after implementing AX [–]
s_{flood}	Share of buildings in the case study area where basement flooding can occur [–]
$s_{I/I\ AX}$	Share of volume of I/I-water to the WWTP after implementing AX [–]
s_{PN}	Share of the WTP that is related to fulfilling treatment requirements for P and N [–]
$s_{rp\ BF}$	Share of basements being flooded during a rainfall with return period rp [–]
s_{ss}	Share of sanitary sewage in CSO spills [–]
t	Year index [–]
T	Time horizon [yr]
t_{rN}	Nitrogen treatment requirement [g/yr]
t_{rP}	Phosphorus treatment requirement [g/yr]
t_{rPN}	Combined PN treatment requirement [g/yr]
t_v	Extra time per vehicle [h]
tr	Traffic flow [vehicles/h]
TV	Time value [MU/h]
$V_{CSO\ A0}$	Annual volume of CSO spills for A0 [m^3/yr]
V_{ex}	Excavation volume [m^3/m]
$V_{I/I\ A0}$	Volume of I/I-water to the WWTP for A0 [m^3/yr]
$WTP_{bf\ b}$	WTP to avoid basement flooding [MU/yr]
WTP_{gs}	Total WTP to reach good status in the recipients [MU/yr]
yrs	Duration of basement flooding discomfort WTP [yr]
ρ_{as}	Asphalt density [kg/m^3]
ρ_{mass}	Density of excavated mass [kg/m^3]
ρ_{pipe}	Pipe density [kg/m]

Appendix B. Methodological details and data used in case study

Distribution of costs and benefits over time

The full annual benefits are included in the CBA after the measure has been constructed. During the construction time, it is assumed that the benefit increases linearly from no benefit before the construction of the measure begins, to full benefit when the construction of the measure is finished.

Choice of probability distributions

Depending on the source of the data, the probability distributions are selected in different ways. Probability distributions from the SHELF-protocol workshops are fitted based on the experts' judgement using SHELF online apps (Oakley, 2022). Additionally, when data series are available, distributions are fitted using the built-in functions in the @Risk program. In other cases, the probability distributions are selected by the project members to fit the uncertainty in the most suitable way. For example, gamma distributions are used for volume of I/I-water and CSO spills, lognormal distributions for costs, and Beta-PERT distributions in cases with limited information about the specific uncertainty.

B1. Reduced internal treatment costs during operation and maintenance

The data used in the case study is presented in Table B1.

Table B1
Data used in case study to calculate B1.

Variable		Unit	Parameter estimate	Distribution	Comment/Reference
$V_{I/I_{A0}}$		m^3/yr	P57: 57,162,884 P68: 67,669,480	Gamma	FCF – Hydraulic model. Including linear increase to $1.25V_{I/I}$ in 2122. The specific percentiles were chosen as they were determined to best describe the flow variations.
$s_{I/I_{AX}}$	A1	-	0.57 (P57) 0.56 (P68)	Uniform	Volume before measure divided by volume after measure (including linear increase to $1.25V_{I/I}$ in 2122) for P57 and P68.
	A2	-	0.88 (P57) 0.89 (P68)	Uniform	Volume before measure divided by volume after measure (including linear increase to $1.25V_{I/I}$ in 2122) for P57 and P68. To include the uncertainty of the impact of relining, a beta-PERT distribution is assigned for the volume of P57 and P68 where min: volume of full impact of measure, most likely: volume of 30% impact, max: volume of no impact.
	A3	-	0.75 (P57) 0.75 (P68)	Uniform	Volume before measure divided by volume after measure (including linear increase to $1.25V_{I/I}$ in 2122) for P57 and P68.
C_{tr}		SEK/m^3	L: 0.62 Q1: 1.00 Median: 1.25 Q3: 1.96 U: 2.50	Lognormal	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).

B2. Reduced costs for GHG emissions for treatment during operation and maintenance

The data used in the case study is presented in Table B2. For data regarding $V_{I/I_{A0}}$ and $s_{I/I_{AX}}$ see Table B1 and for data regarding C_{CO_2} see Table B14.

Table B2
Data used in case study to calculate B2.

Variable	Unit	Parameter estimate	Distribution	Comment/Reference
CI_{tr}	kg CO_2-eq/m^3	Min: 0.03 Most likely: 0.124 Max: 0.22	Beta-PERT	Assessed by project members based on data from the WWTP.

B3. Reduced internal treatment costs for investment in the WWTP

The data used to calculate B3 is presented in Table B3 and Fig. B1.

Table B3
Data used in case study to calculate B3.

Variable		Unit	Parameter estimate	Distribution	Comment/Reference
C_{invA0}		million SEK/year	See used mean values in Figure B1.	Normal / Beta	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023). Increased by approximately 30% by experts at the WWTP due to cost increases.
f_{invAX}	A1	-	0.755	Point value	Estimated by experts at the WWTP based on FDC from FCF – Hydraulic model.
	A2	-	Min: 0.843 Most likely: 0.961 Max: 1	Beta-PERT	Estimated by experts at the WWTP based on FDC from FCF – Hydraulic model. Min: full impact of measure, most likely: 30% impact, max: no impact.
	A3	-	0.861	Point value	Estimated by experts at the WWTP based on FDC from FCF – Hydraulic model.

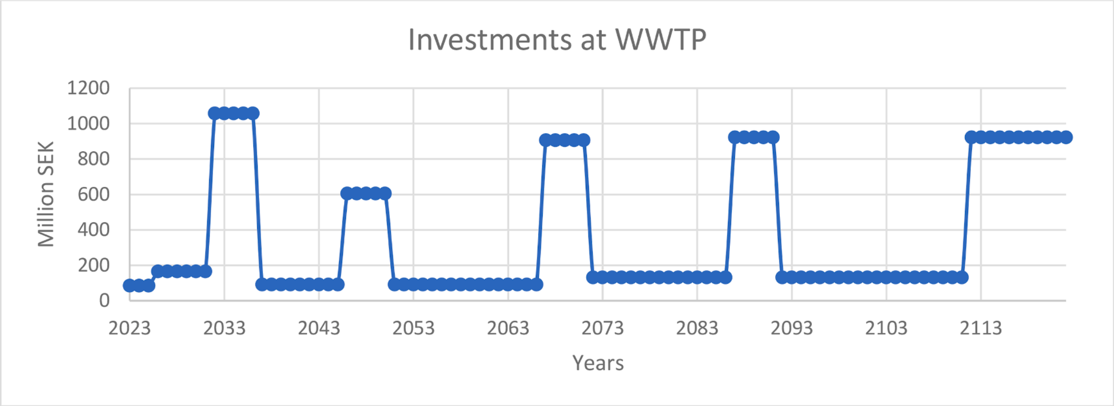

Fig. B1. Investments in the WWTP based on SHELF-protocol workshop in a previous study and increased by approximately 30% by experts at the WWTP for this case study.

B4. Reduced internal electricity cost during pumping

The data used in the case study is presented in Table B4. For data regarding $V_{I/I_{A0}}$and $s_{I/I_{AX}}$ see Table B1. Data used in case study to calculate B1.

Table B4
Data used in case study to calculate B4.

Variable	Unit	Parameter estimate	Distribution	Comment/Reference
E_p	kWh/m^3	L: 0.10 Q1: 0.12 Median: 0.13 Q3: 0.14 U: 0.15	Normal	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
C_p	SEK/kWh	L: 0.76 Q1: 1.36 Median: 1.63 Q3: 2.17 U: 4.34	Lognormal	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).

B5. Reduced costs for GHG emissions for electricity used during pumping

The data used in the case study is presented in Table B5. For data regarding $V_{I/I_{A0}}$ and $s_{I/I_{AX}}$ see Table B1, for E_p see Table B1, and for C_{CO2} see Table B14.

Table B5
Data used in case study to calculate B5.

Variable	Unit	Parameter estimate	Distribution	Comment/Reference
e_{CO2}	kg CO$_2$-eq/kWh	L: 0 Q1: 0.26 Median: 0.35 Q3: 0.44 U: 1	Normal	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).

B6. Reduced internal costs for renewal

Only A2 leads to a higher renewal rate than the reference alternative. Therefore, the benefits of A6 are only included for A2. The data used in the case study is presented in Table B6.

Table B6
Data used in case study to calculate B6.

Variable	Unit	Parameter estimate	Distribution	Comment/Reference
r_{A0} 2023 / 2030 / 2040 / 2050 / 2055 / 2060 / 2070 / 2080 / 2090 / 2100 / 2110 / 2120	-	0.40 / 0.42 / 0.46 / 0.51 / 0.55 / 0.58 / 0.57 / 0.76 / 0.85 / 0.91 / 0.93 / 0.94	Point value	Data retrieved using tool by Wiberg et al. (2011).
r_{AX} – A2 2023 / 2030 / 2040 / 2050 / 2055 / 2060 / 2070 / 2080 / 2090 / 2100 / 2110 / 2120	-	0.40 / 0.41 / 0.39 / 0.34 / 0.31 / 0.33 / 0.38 / 0.44 / 0.51 / 0.58 / 0.66 / 0.74	Point value	Data retrieved using tool by Wiberg et al. (2011).
C_{unit}	SEK/m	μ: 2 548 σ: 4 187	Lognormal	Fitted distribution based on data from previous relining projects from the water utility.
l_{tot}	m	1 437 291	Point value	Length of separate system (City of Gothenburg, 2023).

B7. Reduced costs for GHG emissions for renewal

For data regarding r_{A0}, r_{AX}, and l_{tot} see Table B6, for CI_m see Table B12, and for C_{CO_2} see Table B14. In the case study, the climate impact of performing renewal actions is assumed to be the same as performing relining, i.e. as in A2.

B8. Reduced internal costs of CSO spills because of a reduced need for stormwater treatment

P_{CSO} is calculated according to Eq. (B1):

$$P_{CSO} = s_{ss} \cdot P_{ss} + (1 - s_{ss}) P_{sw} \tag{B1}$$

where s_{ss} is the share of sanitary sewage in CSO spills, P_{ss} the concentration of P in sanitary sewage, and P_{sw} the concentration of P in stormwater.

The data used in the case study is presented in Table B7.

Table B7
Data used in case study to calculate B8.

Variable		Unit	Parameter estimate	Distribution	Comment/Reference
$V_{CSO\ A0}$		m^3/yr	P37: 2290,564 P74: 2937,771	Gamma	FCF – Hydraulic model. Including linear increase to $1.25V_{CSO}$ in 2122.
$s_{CSO\ AX}$	A1	-	0.006 (P37) 0.007 (P74)	Uniform	Volume before measure divided by volume of CSO spills after measure (including linear increase to $1.25CSO_{CSO}$ in 2122) for P37 and P74.
	A2	-	0.953 (P37) 0.949 (P74)	Uniform	Volume of CSO spills before measure divided by volume of CSO spills after measure (including linear increase to $1.25V_{CSO}$ in 2122) for P37 and P74. To include the uncertainty of the impact of relining, a beta-PERT distribution

(*continued on next page*)

Table B7 (*continued*)

Variable	Unit	Parameter estimate	Distribution	Comment/Reference
				is assigned for the volume of P37 and P74 where min: volume of full impact of measure, most likely: volume of 30% impact, max: volume of no impact.
A3	-	0.884 (P37) 0.883 (P74)	Uniform	Volume before measure divided by volume of CSO spills after measure (including linear increase to $1.25CSO_{CSO}$ in 2122) for P37 and P74.
s_{ss}	-	Mean: 0.068	Discrete	Based on data on sanitary sewage in CSO spills in the city of Gothenburg in 2023.
P_{ss}	g P/m^3	L: 2.0 Q1: 4.9 Median: 6.0 Q3: 7.0 U: 9.0	Beta	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
P_{sw}	g P/m^3	L: 0.04 Q1: 0.15 Median: 0.19 Q3: 0.25 U: 0.65	Lognormal	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
C_{tp}	SEK/g	μ: 86.128 σ: 96.171	Lognormal	Based on estimated investment costs for stormwater treatment facilities in the city of Gothenburg.

B9. Reduced external costs of CSO spills because of increased water quality

The concentration of P and N in CSO spills is calculated according to Eq. (B2):

$$PN_{CSO} = \left[s_{ss}\left(P_{ss}\cdot P_{PO_4eq} + N_{ss}\cdot N_{PO_4eq}\right) + (1 - s_{ss})\left(P_{sw}\cdot N_{PO_4eq} + N_{sw}\cdot N_{PO_4eq}\right)\right] \tag{B2}$$

where P_{PO_4eq} is a factor to convert P to PO$_4$-equivalents, N_{ss} the concentration of N in sanitary sewage, N_{PO_4eq} a factor to convert N to PO$_4$-equivalents, and N_{sw} the concentration of N in stormwater.

The treatment requirement for P and N is calculated according to Eq. (B3):

$$t_{rPN} = t_{r_P}\cdot P_{PO_4eq} + t_{r_N}\cdot N_{PO_4eq} \tag{B3}$$

where t_{r_P} is the treatment requirement for P and t_{r_N} the treatment requirement for N.

The data used in the case study is presented in Table B8.

Table B8
Data used in case study to calculate B9.

Variable	Unit	Parameter estimate	Distribution	Comment/Reference
WTP_{gs}	SEK/yr	L: 50,000,000 Q1: 156,000,000 Median: 169,500,000 Q3: 183,000,000 U: 300,000,000	Normal	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
s_{PN}	-	L: 0.05 Q1: 0.15 Median: 0.2 Q3: 0.25 U: 0.35	Beta	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
t_{r_P}	g P/yr	L: 1000,000 Q1: 3000,000 Median: 4000,000 Q3: 5000,000 U: 6000,000	Normal	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
t_{r_N}	g N/yr	L: 25,000,000 Q1: 160,000,000 Median: 240,000,000 Q3: 310,000,000 U: 500,000,000	Weibull	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
P_{PO_4eq}	-	3.07	Point value	As used in Söderqvist et al. (2021).
N_{PO_4eq}	-	0.42	Point value	As used in Söderqvist et al. (2021).
N_{ss}	g N/m^3	L: 17.5 Q1: 22.5 Median: 29.0 Q3: 34.5 U: 42.5	Gumbel type II	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
N_{sw}	g N/m^3	L: 0.70 Q1: 1.55 Median: 1.85 Q3: 2.20 U: 4.25	Gamma	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
s_{ad}	-	Min: 0.05 Median: 0.2 Max: 0.35	Beta	Assessed by project members.

B10. Reduced internal costs of basement flooding because of reduced restoration costs

The data used in the case study is presented in Table B9. Note that A1 only affects basement flooding in the combined system, A3 only in the separate system, and A2 does not affect the number of basement floods. Half of the restoration cost is considered to be internal, and half external and paid for by the private property owner or their insurance companies.

Table B9
Data used in case study to calculate B10.

Variable	Unit	Parameter estimate	Distribution	Comment/Reference
$s_{rp_{BF}}$ Return period 1 / 2 / 5 / 10 / 20 / 50 / 100 / 200 years	-	0 / 0 / 0.04 / 0.16 / 0.32 / 0.56 / 0.68 / 0.72	Point value multiplied by uncertainty $U_{BF}f_{U_{BF}}$, where U_{BF} is P05: 0.8, P25: 0.85, P75: 0.95, P95: 1 (Beta) and $f_{U_{BF}}$ is 0.06 / 0.22 / 0.44 / 0.78 / 0.94 / 1	Assessed following the SHELF-protocol in previous study, see Ohlin Saletti et al. (2023).
s_{flood}	-	Min: 0.01 Most likely: 0.05 Max: 0.5	Beta-PERT	Assessed by project members based on data from water utility regarding previous basement flooding events.
NB_b Single family houses / Apartment buildings / Industry buildings / General service buildings	#	35 561 / 5 978 / 1 021 / 2 978	Point value	Based on drinking water subscribers (City of Gothenburg, 2023).
c_{rb} Single family houses / apartment buildings / Industry buildings / General service buildings	SEK/ flooding	μ: 71 390 σ: 3 394 / μ: 532 451 σ: 42 077 / μ: 541 882 σ: 49 927 / μ: 275 271 σ: 29 447 /	Lognormal	Mean based on The and Skov (2021). Uncertainty estimations based on Rosén and Nimmermark (2018).
s_{com}	-	0.5	Point value	Based on data on previous flooding events in city of Gothenburg.
$dec_{com_{AX}}$ – A1	-	Min: 0.38 Most likely: 0.70 Max: 0.84	Beta-PERT	Interpretation of result from FCF – Hydraulic model.
$dec_{sep_{AX}}$ – A3	-	Min: 0.07 Most likely: 0.63 Max: 0.82	Beta-PERT	Interpretation of result from FCF – Hydraulic model.

B11. Reduced external costs of basement flooding due to reduced discomfort

The data used in the case study is presented in Table B10. Data regarding $s_{rp_{BF}}$ and s_{flood} is presented in Table B9. In the case study, the discomfort from basement flooding in single-family houses and apartment buildings is included. The cost of discomfort for basement flooding in apartment buildings is calculated using the cost of discomfort in single-family houses multiplied by a factor corresponding to the quotient of the restoration cost of apartment buildings and the restoration cost of single-family houses.

Table B10
Data used in case study to calculate B11.

Variable	Unit	Parameter estimate	Distribution	Comment/ Reference
WTP_{bf_b} Single family houses	SEK / household / yr	746	Point value	Based on the study by Torgersen and Navrud (2018). Cost from “wtpB” value concerning respondents with own experience of basement flooding, retrieved from correspondence with Ståle Navrud.
yrs	yrs	P5: 10 P95:30	Normal	Assessed by project members.

C1. Costs for constructing measure

The additional cost for A1 involving stormwater treatment and reconfiguration of the road drainage system is calculated according to Eq. (B4):

$$C_{adA1} = C_{tp} \cdot P_{sw} \cdot r_{rate} \cdot V_{\frac{I}{I}A0} \cdot s_{\frac{I}{I}A1} + f_{ad} \cdot N_{unit_{A1}} \cdot C_{unit\,A1} \tag{B4}$$

Where r_{rate} is the reduction rate of P and f_{ad} a factor representing the share of the total separation cost that should be added to cover costs for separation of the private networks as well as reconfiguration of the road drainage system.

The data used in the case study is presented in Table B11. The costs for A1 and A2 are internal, while regarding A3, the investigation costs are assumed to be internal and the remediation costs are assumed to be external and paid for by the private property owners. Data regarding $V_{I/I_{A0}}$ and $s_{I/I_{AX}}$ can be found in Table B1 and data regarding P_{max} and C_{tp} can be found in Table B7.

Table B11
Data used in case study to calculate C1.

Variable		Unit	Parameter estimate	Distribution	Comment/ Reference
N_{unit}	A1	m	388,146	Point value	Total length of combined system (City of Gothenburg, 2023).

(continued on next page)

Table B11 (*continued*)

Variable		Unit	Parameter estimate	Distribution	Comment/ Reference
	A2	m	1437,291	Point value	Total length of separate system (City of Gothenburg, 2023).
	A3	#	Investigation: 72,490 Remediation: 27,750	Point value	Total number of private properties to be investigated. Number of private properties to be remediated. From input data to FCF – Hydraulic model used by water utility.
C_{unit}	A1	SEK/m	μ: 44,058 σ: 46,343	Lognormal	Fitted distribution based on data from previous separation projects at water utility.
	A2	SEK/m	μ: 2548 σ: 4187	Lognormal	Fitted distribution based on data from previous relining projects at water utility.
	A3	SEK/property	Investigation: P50: 6000 P90: 9000 Remediation: P10: 30,000 P90: 60,000	Lognormal	Estimation based on previous projects in collaboration with pipe investigation actor.
r_{rate}		-	0.5	Point value	Estimation based on (Gothenburg, 2019)
f_{ad}		MU	Min: 0.15 Most likely: 0.21 Max: 0.29	Beta-PERT	(Ljunggren et al., 2011)

C2. Costs for GHG emissions for constructing measure

The total impact per meter is calculated according to Eq. (A4):

$$CI_m = \rho_{pipe} \cdot CI_{pipe} + V_{ex}(P_{ex} \cdot CI_{ex} + (1 - reuse)\rho_{mass} \cdot cap \cdot dist \cdot CI_{tr}) \tag{A4}$$

$$+ A_{as}\left(CI_{as} + d_{as} \cdot \rho_{as} \cdot cap \cdot dist \cdot CI_{tp}\right)$$

where ρ_{pipe} is the density of the pipe, CI_{pipe} the climate impact of the pipe, V_{ex} the excavation volume, P_{ex} the volume that is excavated per hour, CI_{ex} the climate impact of performing the excavation, *reuse* the share of masses that can be reused, ρ_{mass} the density of the excavated masses, *cap* the capacity of the truck transporting masses, *dist* the distance of transportation, CI_{tp} the climate impact of the transportation, A_{as} the area of the asphalt, CI_{as} the climate impact of demolishing the old and paving the new asphalt, d_{as} the depth of the asphalt, and ρ_{as} the density of the asphalt.

Note that it is assumed that A1 is performed completely with open-cut techniques and A2 is performed completely with no-dig techniques. For A3, the excavation length for each property that is remediated is assumed to vary between 10 and 20 m, with a most likely value of 15 m (Beta-PERT distribution).

The data used in the case study is presented in Table B12. For data regarding C_{CO2} see Table B14, and for N_{unit} for A1 and A2 see Table B11.

Table B12

Data used in case study to calculate the climate impact per meter of performed measure (as part of C2).

Variable		Unit	Parameter estimate	Distribution	Comment/Reference
ρ_{pipe}		kg/m	Depends on pipe	Point values	Table values for pipes with different material and diameters.
CI_{pipe}		kg CO_2-eq /m	Depends on pipe	Point values	Environmental product declarations for included pipes.
V_{ex}	A1	m^3/m	P10: 2.80 Mean: 6.66 P90: 16.10	Lognormal	Fitted distribution based on dimensions of excavation work estimated by expert at water utility.
	A3	m^3/m	P10: 1.90 Mean:4.07 P90: 7.55	Gamma	Fitted distribution based on dimensions of excavation work estimated by expert at water utility.
P_{ex}		m^3/h	5	Point value	Estimations from previous study performed for water utility (Norconsult, 2023).
CI_{ex}		kg CO_2-eq/h	36.15	Point value	Estimations from previous study performed for water utility (Norconsult, 2023).
reuse		-	Min: 0 Most likely: 0.6 Max: 1	Beta-PERT	Estimated by expert at water utility.
ρ_{mass}		kg/m^3	Min: 1600 Most likely: 1 800 Max: 2000	Beta-PERT	Estimation by expert at water utility.
cap		kg/truck	34,000	Point value	Estimations from previous study performed for water utility (Norconsult, 2023).
dist		km	Min: 34 Most likely: 50 Max: 75	Beta-PERT	Estimation by expert at water utility.
CI_{tp}		kg CO_2-eq/km	1.417	Point value	Estimations from previous study performed for water utility (Norconsult, 2023).
A_{as}	A2	m^2/m	P10: 1.36 Mean: 2.76 P90: 4.49	Gamma	Fitted distribution based on dimensions of excavation work estimated by expert at water utility.
	A3	m^2/m	P10: 0.58 Mean: 1.48 P90: 2.56	Beta	Fitted distribution based on dimensions of excavation work estimated by expert at water utility.
CI_{as}		kg CO_2-eq/m^2	16.12	Point value	Estimations from previous study performed for water utility (Norconsult, 2023).
d_{as}		m	0.12	Point value	Estimations from previous study performed for water utility (Norconsult, 2023).
ρ_{as}		kg/m^3	2200	Point value	Estimations from previous study performed for water utility (Norconsult, 2023).

C3. Costs for traffic delays during construction of measure

The data used in the case study is presented in Table B13. It is assumed that A3 has no major impact on traffic and hence, no cost for traffic delays is included for that project alternative. For data regarding N_{unit} for A1 and A2 see Table B11.

Table B13
Data used in case study to calculate C3.

Variable		Unit	Parameter estimate	Distribution	Comment/Reference
TV		SEK/h	125	Point value	Based on Fukushima et al., 2022, who present a simplified method of calculating time value based on Swedish transport administration (2020).
t_v		h	Min: 0.0014 Most likely: 0.0083 Max: 0.033	Beta-PERT	Assessed by project members.
tr		vehicles/h	Min: 12.5 Most likely: 208 Max: 1667	Beta-PERT	Assessed by project members.
con_{pace}	A1	m/h	Min: 0.5 Most likely: 0.625 Max: 0.75	Beta-PERT	Estimation by expert at water utility.
	A2	m/h	Min: 10 Most likely: 12.5 Max: 18.75	Beta-PERT	Estimation by expert at water utility.

C4. Social cost of carbon

The SCC can be calculated in various ways and depends on which discount rate is used. The SCC per CO_2-eq in this study is estimated based on the two recent studies by Rennert et al. (2022) and Azar et al. (2023). In the study by Rennert et al. (2022), a discount rate of 2% is used, which is the discount rate used in the sensitivity analysis of the case study, and the SCC is therefore set to 1.88 SEK/CO_2-eq for this discount rate (P05: 0.45 SEK and P95: 4.19 SEK, converted from USD2020 to SEK2023). Note that the SCC distribution reported by Rennert et al. (2022) includes negative values; however, in this study the SCC is truncated at a lower bound of 0.01 to exclude such values. The restriction to positive values serves two purposes: it allows for the application of a yearly price increase as proposed by Azar et al. (2023) and ensures consistency with the SCC estimates reported in the same study. Accordingly, the increase of SCC over time, is based on Azar et al. (2023) where the SCC for a 2% discount rate is similar to the one presented by Rennert et al. (2022), and increases to 6.08 SEK (converted from USD2020 to SEK2023) in year 2100. The uncertainty interval is assumed to be the same over the time horizon.

For the discount rate of 3.5%, results from a sensitivity analysis by Azar et al. (2023) are used where the SCC with a discount rate corresponding to 3.5% is 0.42 times the SCC that corresponds to the 2% discount rate. The factor of 0.42 is therefore multiplied by the SCC used for the discount rate of 2% to get the SCC for the 3.5% discount rate.

The data used for SCC (C_{CO_2}), in the case study is represented by skew normal distributions andare summarised in Table B14.

Table B14
Data for SCC used in case study.

Variable	Unit	Parameter estimate	Distribution	Comment/Reference
C_{CO_2} r = 2.0% dec	SEK/kg CO2-eq	$\xi = 0.671$ $\omega = 1.8$ $\alpha = 3.41$ Truncated at 0.01	Skew normal	(Azar et al., 2023; Rennert et al., 2022). A linear annual increase of 1.4% is added to reach the cost of 6.08SEK year 2123.
C_{CO_2} r = 3.5%	SEK/kg CO2-eq	$\xi = 0.282$ $\omega = 0.754$ $\alpha = 3.41$ Truncated at 0.01	Skew normal	(Azar et al., 2023; Rennert et al., 2022). A linear annual increase of 2.1% is added.

The social costs of CO_2 emissions are, to some extent, internalised in, e.g. energy prices through policy instruments, such as the EU emissions trading system or the Swedish CO_2 tax. Since quantifying the exact size of this internalisation is beyond the scope of this study, it has been assumed that the average internalised cost of a CO_2-eq is 1 SEK in Sweden. This corresponds roughly to the price of emissions rights and the CO_2 tax in 2023 (Swedish EPA, 2024). To avoid double counting, the inclusion of the SCC in the analysis has been combined with subtracting a cost of 1 SEK times the CO_2-eq for cost/benefit C2, B2, B5, and B7 from internal cost/benefit C1, B1, B4, and B6.

Data availability

Data will be made available on request.

References

ABVA, 2006. Lagen om allmänna vattentjänster, 2006:412 (Swedish legislation text). https://rkrattsbaser.gov.se/sfst?bet=2006, 412.

Ambulkar, A., Nathanson, J.A., 2026. Wastewater treatment. Encycl. Br. https://www.britannica.com/technology/wastewater-treatment.

Aven, T., 2012. *Foundations of Risk Analysis: Second Edition* [Book]. John Wiley & Sons.

Azar, C., Martín, J.G., Johansson, D.J., Sterner, T., 2023. The social cost of methane. Clim. Change 176 (6), 71. https://doi.org/10.1007/s10584-023-03540-1.

Ballerup Municipality (n.d.). Separatkloakering. https://ballerup.dk/borger/bolig-vand-varme/vand-afloeb/separatkloakering.

Bedford, T., Cooke, R., 2001. Probabilistic Risk analysis: Foundations and Methods. Cambridge University Press.

Beheshti, M., Sægrov, S., 2018. Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim, Norway [Article]. Urban Water J. 15 (1), 1–8. https://doi.org/10.1080/1573062X.2017.1363253.

Beheshti, M., Saegrov, S., Ugarelli, R., 2015. Infiltration/inflow assessment and detection in urban sewer system. Vann 01, 24–34. http://hdl.handle.net/11250/2598406.

Boardman, A.E., Greenberg, D.H., Vining, A.R., Weimer, D.L., 2018. *Cost-benefit analysis: Concepts and Practice* (Fifth Edition ed.). Cambridge University Press.

City of Gothenburg, 2023. *Annual Report 2022 - Kretslopp och vattennämden*. Department of Sustainable Waste and Water. City of Gothenburg.

Davalos, P., Humphrey, G., Eagle, S., Roque, R., Bedoya, J., Edwards, D., Torrealba, F., Perez, J., Dvorak, A., 2018. Cost effective infiltration and inflow analysis and remediation efforts in Miami-Dade county [Conference Paper]. In: Proceedings of the Water Environment Federation, pp. 2994–3023, 2018(12).

Derx, J., Müller-Thomy, H., Kılıç, H.S., Cervero-Arago, S., Linke, R., Lindner, G., Walochnik, J., Sommer, R., Komma, J., Farnleitner, A.H., Blaschke, A.P., 2023. A probabilistic-deterministic approach for assessing climate change effects on infection risks downstream of sewage emissions from CSOs [Article]. Water Res. 247. https://doi.org/10.1016/j.watres.2023.120746. Article 120746.

Diogo, A.F., Barros, L.T., Santos, J., Temido, J.S., 2018. An effective and comprehensive model for optimal rehabilitation of separate sanitary sewer systems [Article]. Sci. Total Environ. 612, 1042–1057. https://doi.org/10.1016/j.scitotenv.2017.08.315.

European Union, 2024. Directive of the European parliament and of the council concerning urban wastewater treatment. https://data.consilium.europa.eu/doc/document/PE-85-2024-INIT/en/pdf.

Franz, T., 2007. *Spatial classification methods for efficient infiltration measurements and transfer of measuring results* [Doctoral dissertation, Dresden University of Technology]. https://tinyurl.com/w95ne9js.

Future City Flow, 2022. http://www.futurecityflow.se/.

Fukushima, N., Ridderstedt, I., & Bondemark, A. (2022). Internalizing social costs in public procurement of road maintenance. [Unpublished manuscript].

Gothenburg, C.O. (2019). Åtgärdsförslag dagvatten.

Hansen, A., Moussavi, S., Dvorak, B., 2024. Reducing infiltration and inflow in small collection systems: environmental, economic, and additional impacts [Article]. J. Environ. Eng. (U. S.) 150 (1). https://doi.org/10.1061/JOEEDU.EEENG-7446. Article 05023009.

HM Treasury, 2026. The Green Book: UK Government Guidance On Appraisal. U. Government. https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-government.

ISO, 2018. *Risk Management - Guidelines* (ISO 31000:2018, Issue. International Organization for Standardization. https://www.iso.org/obp/ui/. #iso:std:iso:31000:ed-2:v1:en.

Johansson, P.-O., Kriström, B., 2018. Cost–Benefit Analysis. Cambridge University Press. https://doi.org/10.1017/9781108660624.

Karpf, C., Krebs, P., 2011. Quantification of groundwater infiltration and surface water inflows in urban sewer networks based on a multiple model approach. Water. Res. 45 (10), 3129–3136. https://doi.org/10.1016/j.watres.2011.03.022.

Kaushal, V., Najafi, M., 2020. Comparative analysis of environmental and social costs of trenchless cured-in-place pipe renewal method with open-cut pipeline replacement for sanitary sewers. J. Pipeline Syst. Eng. Pract. 11 (4), 04020037. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000480.

Korving, H., Van Noortwijk, J.M., Van Gelder, P.H.A.J.M., Clemens, F.H.L.R., 2009. Risk-based design of sewer system rehabilitation. Struct. Infrastruct. Eng. 5 (3), 215–227. https://doi.org/10.1080/15732470601114299.

Lee, J.H., Baek, C.W., Kim, J.H., Jun, H.D., Jo, D.J., 2009. Development of a decision making support system for efficient rehabilitation of sewer systems. Water Resour. Manag. 23, 1725–1742. https://doi.org/10.1007/s11269-008-9349-2.

Ljunggren, O., Annika, M., Jansson, J., 2011. *Ekonomiska konsekvenser av att bygga bort det kombinerade systemet*. K. o. v. Göteb. stad.

Lundblad, U., Backö, J., 2014. *Juridisk och ekonomisk hantering av tillskottsvatten som sker till spillvattenförande ledning innanför förbindelsepunkt (Legal and financial management of water injections that takes place on the privately owned drains)* (2014-11). Sven. Vatten AB. https://vav.griffel.net/filer/SVU-rapport_2014-11.pdf.

Malm, A., Horstmark, A., Jansson, E., Larsson, G., Meyer, A., Uusijärvi, J., 2011. Handbok i förnyelseplanering av VA-ledningar (Guidelie for renewal planing of water and wastewater networks). Sven. Vatten AB: Stockh. Swed. 122.

Norconsult, 2023. PM Klimatberäkning - Förstudie VA-försörjning Norra Hisingen. City of Gothenburg.

Oakley, J.E. (2022). Expert elicitation. Retrieved March 25 from http://www.jeremy-oakley.staff.shef.ac.uk/project/elicitation/.

Ohlin Saletti, A., 2021. Infiltration and inflow in wastewater sewer systems - A literature review on risk and decision support. https://tinyurl.com/3cp9bw25.

Ohlin Saletti, A., Lindhe, A., Söderqvist, T., Rosén, L., 2023. Cost to society from infiltration and inflow to wastewater systems. Water Res. 229, 119505. https://doi.org/10.1016/j.watres.2022.119505.

Ohlin Saletti, A., Rosén, L., Lindhe, A., 2021. Framework for risk-based decision support on infiltration and inflow to wastewater systems. Water (Basel) 13 (17), 2320. https://doi.org/10.3390/w13172320.

OMB. (2023). Circular No. A-4: regulatory analysis. https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/11/CircularA-4.pdf.

Perez, G., Gomez-Velez, J.D., Grant, S.B., 2024. The sanitary sewer unit hydrograph model: a comprehensive tool for wastewater flow modeling and inflow-infiltration simulations. Water Res. 249, 120997. https://doi.org/10.1016/j.watres.2023.120997.

Perry, W.B., Ahmadian, R., Munday, M., Jones, O., Ormerod, S.J., Durance, I., 2024. Addressing the challenges of combined sewer overflows [Review]. Environ. Pollut. 343. https://doi.org/10.1016/j.envpol.2023.123225. Article 123225.

Rennert, K., Errickson, F., Prest, B.C., Rennels, L., Newell, R.G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., Smith, D., Cromar, K., Diaz, D., Moore, F.C., Müller, U.K., Plevin, R.J., Raftery, A.E., Ševčíková, H., Sheets, H., …Anthoff, D., 2022. Comprehensive evidence implies a higher social cost of CO2. Nature 610 (7933), 687–692. https://doi.org/10.1038/s41586-022-05224-9.

Rosén, L., Nimmermark, J., 2018. FloodMan - sustainable flood management assessment tool. Ett verktyg för samhällsekonomisk analys och hållbarhetsanalys av översvämningsskydd. Göteborgs Stad. Sweco Environ. AB Uppdragsnummer, 13002424Updated 2021.

Rudersdal Municipality [n.d.]. *Separering af fælleskloakerede områder i Rudersdal Kommune*. https://rudersdal.dk/borger/affald-miljoe-og-klima/klimaindsatser/separering-af-faelleskloakerede-omraader-i-rudersdal.

Scholten, L., Scheidegger, A., Reichert, P., Mauer, M., Lienert, J., 2014. Strategic rehabilitation planning of piped water networks using multi-criteria decision analysis. Water Res. 49, 124–143.

Sola, K.J., Bjerkholt, J.T., Lindholm, O.G., Ratnaweera, H., 2018. Infiltration and Inflow (I/I) to Wastewater Systems in Norway, Sweden, Denmark, and Finland [Article], 10. Water. https://doi.org/10.3390/w10111696. Article 1696.

Sola, K.J., Bjerkholt, J.T., Lindholm, O.G., Ratnaweera, H., 2020. Analysing consequences of infiltration and inflow water (I/I-water) using cost-benefit analyses. Water Sci. Technol. https://doi.org/10.2166/wst.2020.395.

Sola, K.J., Bjerkholt, J.T., Lindholm, O.G., Ratnaweera, H., 2021. What effect does rehabilitation of wastewater pipelines have on the share of infiltration and inflow water (I/I-water)? Water (Basel) 13 (14), 1934. https://doi.org/10.3390/w13141934.

Staufer, P., Scheidegger, A., Rieckermann, J., 2012. Assessing the performance of sewer rehabilitation on the reduction of infiltration and inflow. Water Res. 46 (16), 5185–5196. https://doi.org/10.1016/j.watres.2012.07.001.

Swedish EPA. (2024, 2024-04-05). Statistik och uppföljning. https://www.naturvardsverket.se/vagledning-och-stod/utslappshandel/statistik-och-uppfoljning/.

Swedish transport administration. (2020). Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 7.0. https://tinyurl.com/3889vj3e.

Swedish transport administration, 2024. Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn ASEK 8.0. https://tinyurl.com/5etret49.

Swedish Water. (2016). P110 del 1 Avledning av dag-, drän- och spillvatten. http://vav.griffel.net/filer/P110_del1_web_low_180320.pdf.

Söderqvist, T., Brinkhoff, P., Norberg, T., Rosén, L., Back, P.-E., Norrman, J., 2015. Cost-benefit analysis as a part of sustainability assessment of remediation alternatives for contaminated land. J. Environ. Manage 157, 267–278.

Söderqvist, T., Nathaniel, H., Franzén, D., Franzén, F., Hasselström, L., Gröndahl, F., Sinha, R., Stadmark, J., Strand, Å., Ingmansson, I., Lingegård, S., Thomas, J.-B., 2021. Cost–benefit analysis of beach-cast harvest: closing land-marine nutrient loops in the Baltic Sea region. Ambio. https://doi.org/10.1007/s13280-021-01641-8.

The, S., Skov, M., 2021. Kostnadsanalys av översvämningsskydd - 7 områden längs Skånes kust (Cost analysis of flood protection along the coast of Skania). L. Skåne. https://tinyurl.com/2rrmauea.

Torgersen, G., Navrud, S., 2018. Singing in the rain: valuing the economic benefits of avoiding insecurity from urban flooding. J. Flood Risk Manag. 11 (4), e12338. https://doi.org/10.1111/jfr3.12338.

Vallin, H., 2016. *Utvärdering av multikriterieanalys som verktyg för spatial resursallokering av dagvattenåtgärder för tillskottsvatten i spillvattennät (Evaluation of multi criteria analysis as a tool for spatial resource allocation of stormwater measures for inflow and infiltration to the sewage water system)* Uppsala University]. https://tinyurl.com/yckjh9vy.

Wang, M., Zhang, M., Shi, H., Huang, X., Liu, Y., 2019. Uncertainty analysis of a pollutant-hydrograph model in assessing inflow and infiltration of sanitary sewer systems. J. Hydrol. 574, 64–74. https://doi.org/10.1016/j.jhydrol.2019.04.011.

Wiberg, N., Malm, A., & Svensson, G. (2011). Förnyelsebehov avloppsledningar (Need of renewal wastewater pipes) - Tool. Swedish water. https://vattenbokhandeln.svensktvatten.se/produkt/fornyelseplanering-av-va-nat-sammanfattning-av-rapporterna-2011-12-13-och-14/.